special report

Engineering Research Institute

CHEMICAL STABILIZATION AND

PHYSICOCHEMICAL PROPERTIES OF SOILS

Iowa Highway Research Board Project HR-97
Engineering Research Institute Project 505-S

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Iowa State University

Ames, Iowa

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SPECIAL NOTE

This Special Report contains a summary of Final Report including an amendment on screening tests and a progress report on use of epoxies for soil stabilization. Two progress reports namely "Treatment of a Crushed Stone with a Quaternary Ammonium Chloride" and "Water Vapor Sodium Montmorillonite Interaction" previously submitted as part of the final report are not included with this report. These two reports are being published by HRB and will be available to interested parties.

FINAL REPORT

CHEMICAL STABILIZATION AND CHEMICAL PROPERTIES OF SOILS

Iowa Highway Research Board Project HR-97

Engineering Research Institute Project 505-S

This project was initiated to gain a better understanding of the phenomena which affect the engineering behavior of soils containing colloidal size particles and to find chemical methods of treatment which could improve the engineering performance of such soils.

The structural strength of clayey soils has been attributed to bonds, congealing, the development of preferred orientations and extrusion of waterfilms from between fine mineral particles. A true explanation of these factors is possible through an understanding of the colloidal phenomena governing the behavior of soils.

One of the main objectives of this investigation was to investigate the colloidal behavior of clays through their interaction with water by X-ray diffraction and water vapor adsorption isotherm experiments. Since a research of this nature lends itself only to long term investigations the original plan was made for three years. The contract, however, was drawn for two years with the understanding only that work completed in the two-year period would be reported. This Final Report, therefore, presents representative data and methods used, and conclusions from the research on chemical stabilization and physico chemical properties of soils for the two-year period ending October 31, 1965.

More complete information on the separate phases has been reported previously in a series of "Progress Reports". These Progress Reports are attached to this Final Report for ready reference.

I. USE OF ORGANIC CATIONIC WATERPROOFERS FOR GRANULAR SOILS CONTAINING SMALL AMOUNTS OF CLAY

Treatment of a Crushed Stone with a Quaternary Ammonium Chloride

The effect of a quaternary ammonium salt on the stability of a base course material treated with varying percentages of the salt and exposed to the action of water was determined by investigating its shearing strength.

Materials:

(1) Quaternary ammonium salt: The quaternary ammonium salt used was dioctadecyl di-methyl ammonium chloride produced by Armour Industrial Chemical Co. under the trade name of Arquad 2HT.

(2) Granular base course material: The granular base course material used was a crushed rock obtained from a quarry located in Taylor County, Iowa, 1/2 mile east of the town of Bedford and just south of Highway 2. The crushed rock was classified as A-1-a.

This material, although it meets the AASHO specifications for base courses, was found to be very susceptible to the action of water, as indicated by its soaked CBR value of 33%.

Preliminary investigation:

Preliminary investigations were conducted to establish the maximum dry densities and optimum moisture contents for the major investigation. Curing studies were also conducted by air-drying the specimens

to establish the residual moisture contents at which the soaked specimens would give the maximum immersed strength.

The Standard Proctor Density and the Standard Optimum Moisture Content decreased with increasing amounts of Arquad 2HT. The maximum dry densities decreased from 130.5 pcf at zero percent Arquad 2HT to 127.0 pcf at 0.10% Arquad 2HT. The optimum moisture contents decreased from 10.7% at zero percent Arquad 2HT to 10.2% at 0.10% of Arquad 2HT.

The effects of curing on the strength of a specimen were investigated by using soaked CBR tests. These tests indicated that the maximum immersed strength occurs at a moisture loss of about 4.5 - 5.8% during air-drying. All specimens for the major investigation were air-dried to within this moisture loss range.

Major investigation:

The specimens for the major investigation were molded by vibrational compaction to near Standard Proctor Density at the optimum moisture contents previously established. The specimens were confined in rubber membranes, and then were cured by air-drying. They were soaked vertically in water which worked into the soil from the bottom up for about 48 hours, and were tested by undrained quick triaxial shear test without pore pressure measurements. The results obtained are summarized in Table 1.

Table 1. Effect of Arquad 2HT on apparent cohesion* and angle of shearing resistance* of the granular base course material.

Arquad 2HT content, %	Apparent cohesion, psi	Angle of shearing resistance, degrees
0	11.5 ± 6.5	16.5 ± 5
0.01	4 ± 2	23.1 ± 2.6
0.03	7.5 ± 1.5	22.7 ± 1.2
0.05	6 ± 2	24.3 ± 1.3

* Evaluated using total principal stresses determined by undrained, quick triaxial tests.

Discussion and conclusions:

The apparent cohesion and the angle of shearing resistance are, unlike the true cohesion and the angle of internal friction, neither independent variables of the shearing resistance nor basic properties of a soil; they depend extensively on the pore pressure (neutral stress) developed within the stressed soil water system. The determination of true cohesion and angle of internal friction and their use require careful examination of neutral stresses which, in certain cases such as road base courses, may be unpredictable, undeterminable, and inconsistant due to the heterogeneous nature of the material and the variable nature of such field conditions as loading and seepage patterns. The apparent cohesion and angle of shearing resistance however, under prevailing conditions determine the shearing resistance of the material (soil-water system) according to the law of shearing resistance. For example, prevailing conditions for a material protected against the ingress of water do not allow the development of significant and fluctuating pore pressure, resulting in high and stable values of

apparent cohesion and/or angle of shearing resistance. In other words these parameters indicate the stability attained by a treatment. For these reasons and because of its simplicity the undrained quick test was used.

It was expected that waterproofing additives, by controlling the impregnation of the material by water, would reduce and stabilize pore pressure development and thus eliminate high magnitudes and fluctuations of developed neutral stresses which result in high shearing resistance and stability.

The addition of Arquad 2HT to the granular base material caused a significant reduction in the fluctuations of both apparent cohesion and angle of shearing resistance (Table 1). A possible explanation of the mechanism of waterproofing action of Arquad 2HT on water susceptible granular materials is that a granular material is made up of aggregate-size structural units with large pores between these units. The structural units are particles of gravel, sand, and silt cemented together by clay. When the material is untreated, water penetrates into the large pores and into the structural units. This may cause segregation of fines and may increase the pore pressure within the structural units.

The water in large pores is assumed to have little effect on the neutral stresses affecting the shear strength of a granular material but the water within the pores of structural units does. Due to heterogeneity of the granular material augmented by the action of water (segregation of fines causing a sort of plug against the entrance of water) moisture absorption and the pore pressures within these

structural units of untreated material may vary. These cause significant fluctuations in shearing strengths of different samples or of different parts of the base of a road. These fluctuations are evidenced by high values of 95% confidence limits.

When the material is treated with Arquad 2HT, the aggregation of material is increased due to coagulant action of Arquad 2HT, leading to reduced segregation during compaction (better homogeneity); and the structural units are waterproofed against the penetration of water. Water then enters only the large pores. The pore pressure within the structural units is limited to an equilibrium value that is far less than the maximum pore pressure developed in soaked untreated material. In other words, Arquad 2HT stabilizes the structural units of the granular material to make it homogeneous, to prevent the segregation of fines, and to limit the amount of moisture and the pore pressure under extremely wet conditions. This results in a maximum non-fluctuating shear strength.

The following conclusions are based on the data obtained:

Arquad 2HT is an effective additive for improving the shear strength of a water susceptible granular material under adverse moisture conditions. Without treatment the shear strength of the material varies greatly. The average shear strength of the untreated material is significantly lower than that of treated material. There is little variation in the shear strength of treated material under these extreme moisture conditions. If the lower limits of the apparent cohesion and the angle of shearing resistance are taken as the safe values, the following is obtained for the material studied in this investigation:

Treatment	Apparent cohesion, psi		Angle of shearing resistance, degrees	
	Average	Safe	Average	Safe
None	11.5 ± 6.5	5	16.5 ± 5	11.5
Arquad 2HT, 0.03%	7.5 ± 1.5	5	22.7 ± 1.2	21.5

II. ALTERNATIVE WETTING AND DRYING, AND SWELLING OF CLAYS DUE TO ADSORPTION OF WATER VAPOR

(a) Water Vapor Sodium Montmorillonite Interaction

Sorption isotherm and X-ray diffraction experiments were performed on a sodium montmorillonite and the data obtained were used to deduce information for interpretation of the isotherms, the manner in which water enters between clay layers, free energy changes on adsorption and swelling pressures.

Materials:

Homoionic sodium montmorillonite was prepared from a commercial Wyoming bentonite, Volclay-SPV, by ion exchange.

Sorption isotherms:

Three successive adsorption-desorption isotherms of water vapor on sodium montmorillonite were determined gravimetrically with a McBain-Bakr quartz spring balance in an adsorption chamber where temperature and vapor pressure could be controlled. The temperature was maintained

at 24.4° C; the initial pressure of the system was 10^{-5} mm Hg.

The adsorption isotherm data were used for determination of BET parameters and to follow, by Bangham's free energy equation, the free energy changes due to adsorption of water vapor.

X-ray diffraction:

First order basal spacing and line width variations with continually varying relative pressure of water vapor were determined by X-ray diffraction techniques with the sodium montmorillonite sample in an adsorption chamber built to fit on a General Electric XRD-5 Diffractometer. Temperature and vapor pressure in the adsorption chamber were controlled. Basal spacing data was compared with that reported by others. Basal spacing and line width data were correlated with sorption isotherm and free energy data.

Results and conclusions:

1. The change in average basal spacings of sodium montmorillonite takes place in a continuous but non-uniform manner with changes in relative pressure; continuity is due to the simultaneous existence of varying numbers of molecular layers of interlayer water. Expansion occurs in three increments; basal spacing and line width data show average spacings correspond with an integral number of molecular layers of water just prior to each increment of expansion.

2. The relationship between relative humidity and the basal spacing of sodium montmorillonite is dependent upon: a) the source and method of preparation of the sample, b) the initial conditions of

the sample at the start of tests, and c) whether data are collected during adsorption or desorption.

3. Basal spacing, line width and free energy change data give evidence that the interlayer water builds up in a laminar manner.

4. Adsorption isotherms are more closely reproduced on successive adsorption-desorption runs than are desorption isotherms.

5. The hysteresis displayed by the sorption isotherms is due in part to the formation of a thixotropic structure at high relative pressures, and in part to attractive interaction forces between sodium montmorillonite platelets.

6. X-ray diffraction data and BET plots indicate that the BET parameter q_m obtained reflects adsorption only on the external surfaces of the material; apparently sodium montmorillonite prepared from Wyoming bentonite (Volclay) is unique in this respect.

7. The relationship between free energy changes and relative pressure and the X-ray diffraction data for the adsorption of water vapor on sodium montmorillonite allows separation of the free energy change into two components, one due to adsorption on the external surfaces and one due to adsorption on and separation of internal surfaces.

8. Free energy data and X-ray data show that the expansion energy (free energy change due to adsorption on and separation of internal surfaces) during formation of the second layer of interlayer water is approximately the same as that for formation of the first layer; the change during formation of the third layer is substantially less than those for the other two.

9. Free energy data and X-ray data permit the estimation of swelling pressures exerted by sodium montmorillonite due to the uptake of interlayer water when the material is in contact with saturated vapor. The swelling pressure exerted when the platelet separation is zero is about 325 tons/ft^2. The pressure exerted when one molecular layer of water separates clay platelets is about 200 tons/ft^2; when two molecular layers of water separate platelets it is about 50 tons/ft^2.

(b) Water Vapor Calcium Montmorillonite Interaction

Experiments for this phase of the study have been 90% completed and the work is still under progress. Major Donald Senich, a self-sponsored graduate student has been assigned to this investigation to complete his Ph.D. research. The work will be completed in March 1966 and a joint "Special Report" for projects HR-97 and HR-106 will be submitted to the Iowa Highway Research Board. If the report is submitted for publication permission will be requested from the Iowa Highway Research Board and the Bureau of Public Roads.

Materials:

Homoionic calcium montmorillonite was prepared from a commercial Wyoming bentonite, volclay-SPV, by ion exchange.

Sorption isotherms and rate of sorption:

Two successive adsorption-desorption isotherms of water vapor on

calcium montmorillonite were determined gravimetrically with a Cahn electrobalance in an adsorption chamber where temperature and vapor pressure could be controlled. The temperature was maintained at 25.0°C; the initial pressure of the system was 10^{-5} mm Hg.

The adsorption isotherm data are being used for correlating moisture gain with interlayer expansion, and for determination of BET parameters and the free energies of immersion and wetting.

X-ray diffraction:

All orders of basal spacings, line width and relative intensity variations with continually varying relative pressure of water vapor were determined by X-ray diffraction experiments with the calcium montmorillonite sample in the adsorption chamber maintained at 25°C. Basal spacings data are being compared with those reported in the literature. Basal spacings, relative intensities and line width data are being correlated with sorption isotherm and free energy data.

Results and some tentative conclusions:

1. The change in average basal spacings of calcium montmorillonite takes place in a continuous but non-uniform manner with relative vapor pressure of water; continuity is due to the simultaneous existence of varying number of molecular layers of interlayer water and/or warping of montmorillonite sheets. Expansion occurs in five increments; basal spacing and line width data show that three of the average spacings correspond to an integral number of molecular layers of water, whereas the other two spacings do not correspond to integral number of layers.

The latter two spacings probably correspond to space occupied by hydrated calcium ions.

2. The relationship between relative humidity and the basal spacing of calcium montmorillonite depends on whether data is collected during adsorption or desorption.

3. The hysteresis loop displayed by sorption isotherms closes at a relative pressure range of 0.1 - 0.2.

4. X-ray diffraction data and BET plots indicate that BET parameter q_m obtained at relative pressure range of 0 - 0.02 reflects adsorption on the external surfaces and q_m parameter obtained at relative pressure range of 0.11 - 0.27 reflects adsorption on total surfaces.

5. Total free energy of immersion of calcium montmorillonite is 70 ergs/cm^2, almost twice that of sodium montmorillonite.

III. SCREENING STUDIES

Soil Stabilization with Epoxy Resin

Epoxy resins, urea-formaldehyde, polystyrene-spent sulfite liquor and reclaimed rubber were subjected to screening studies. Of these additives epoxy resins gave far better results. Epoxy resin was, therefore, investigated in detail.

Materials:

1. Soils: Four soils were used in this investigation. These

were a silty loam, two silty clays and one fine sand.

2. Epoxy: The epoxy system used was a commercial product from Shell Chemical Co. sold under the trade name of Guardkote.

Methods of investigation:

1. Screening test: The first phase of the investigation was devoted to a screening of various resin to hardness ratios and various mixing orders utilizing 1-inch high by 1/2-inch diameter specimens with two of the soils. Specimens were molded by static loading to maximum density at optimum moisture content. Two to four was found to be the most effective resin to epoxy ratio. The most effective mixing order was: first mixing the necessary amount of water with the dry solids then adding prepared epoxy system to the moist soil and mixing again.

2. Main study: Various percentages of lime and epoxy system were incorporated with all four soils. Specimens 2 inches high by 2 inches in diameter were molded and cured by air drying for 7 days. The effects of the additives on optimum liquid content, dry density and immersed strength were determined. The best combinations were selected for frost susceptibility investigations by using Iowa Freeze-Thaw Method. One of the soils was further investigated as a surface course material by traffic simulation and beam tests.

Results and conclusions:

1. After the soils were stabilized with various percentages of epoxies all were found suitable as base course materials. Traffic simulator tests have shown that the resistance of epoxy treated soils

against the abrasive action is excellent, therefore epoxy or epoxy lime stabilized soils may be tried as a road surface material.

2. The effectiveness of epoxy treatment depends on the clay content. High clay content gives the least satisfactory results. The epoxy stabilization is most effective for the friable loess.

3. All soils used in the investigation were improved in immersed strengths by the addition of lime to the soils to be stabilized by epoxy.

4. The epoxy affects soils in two ways: (1) reduces the moisture affinity of clays by surface chemical action, and (2) imparts cementation, thereby producing semi-rigid soil framework. The lime is believed to be an agent which causes the cured epoxy to be a more ductile material. This may be responsible for increased immersed strengths of soil specimens.

5. The higher the curing temperature, the faster the setting of epoxy stabilized soil. Curing temperatures between $30^{\circ}F$ and $104^{\circ}F$ were found most practical for curing epoxy stabilized soil specimens. The short curing time for epoxy makes it an ideal stabilizing agent for emergencies. The epoxy dune sand mixtures with lime could be hardened at $80^{\circ}F$ in half an hour.

6. Because of the high cost ($0.60 per lb.) epoxy compares unfavorably with other methods of soil stabilization. However, the cost of epoxies has shown a very rapid decline. If this trend continues epoxy may be an economical stabilization agent for the future.

AMENDMENT TO THE FINAL REPORT

Results of Screening Studies

Preliminary screening of urea-formaldehyde, urea-formaldehyde-spent sulfite liquor, polystyrene-spent liquor, reclaimed rubber, and reclaimed rubber-spent sulfite liquor were done by using the screening test developed earlier at Iowa State University[1].

Sample

The test utilizes 1 inch high by 1/2 inch diameter test specimens. This small size results in considerable savings of time and materials, and is sufficiently large for clays, silts, and fine sands. Only the portion of the soil which passes the No. 40 sieve is used, since large particles and conglomerates would unduly influence the characteristics of the specimens. The minus No. 40 portion, with its higher percentages of clay-size material and increased surface area, provides a more rigorous test of effectiveness.

Apparatus

The molding apparatus consists of a lever arrangement by which the soil mixture is compressed by hand into a cylindrical mold.

The unconfined compression testing machine automatically plots stress versus strain by means of a lever system which is controlled by the relative motion of parts of the machine during loading. This machine was modified after the British Building Research Station apparatus.

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[1]Roderick, G. L.,Demirel, T. and Davidson, D. T., Use of phosphoric acid and furfuryl alcohol for soil stabilization. Proc. Iowa Academy of Science, V. 69, pp. 370-379, 1962.

Procedures

The soil, additives, and enough water to bring the sample approximately to optimum liquid content, are thoroughly mixed by hand with a spatula. The required amount of the mixture to give a 1" by 1/2" specimen of the desired density is placed in the mold and compressed by static pressure on the lever. The sample is then extruded and cured. After curing, one-half of the samples are tested for unconfined compressive strength; the other half are immersed in water for 24 hours and tested.

Results

The results obtained primarily reflect the cohesive strength of the soil-additive system. The test after immersion reflects waterproofing ability of the stabilizer.

Soil: The soil subjected to the screening tests was a silty clay loess. It contained 80 percent silt and 20 percent clay.

Urea formaldehyde: The liquid urea-formaldehyde resin used in this study was Foramine 21-019 produced by Reichhold Chemicals, Inc. Catalysts used were ammonium chloride and phosphoric acid. Satisfactory and consistent strengths were obtained with 9 percent urea formaldehyde and 1 percent phosphoric acid (average dry strength 300 psi, average immersed strength 200 psi) and 9 percent urea formaldehyde and 2 percent ammonium chloride (average dry strength 500 psi, average immersed strength 200 psi). Samples made with lower percentages of these additives showed sudden drops in strength. Addition of spent sulfite liquor (from 2 to 8 percent) lowered both the dry and the immersed strengths as much as 50 percent. Further investigation of urea-

formaldehyde, soil systems is suggested.

Polystyrene-spent sulfite liquor: Earlier investigations at Iowa State had shown that a benzene solution of polystyrene to be an effective soil stabilization agent[1]. The purpose of the present screening investigation was to find out if spent sulfite liquor could replace part of the polystyrene. The polystyrene used was plaspan 8 produced by The Dow Chemical Company. Plaspan 8 was desolved in benzene before adding it to the soil. Addition of spent sulfite liquor increased the dry strength slightly but reduced the immersed strength. Addition of 4 percent spent sulfite liquor increased the dry strength of the soil stabilized with 9 percent polystyrene from 1400 psi to 1700 psi but reduced its immersed strength from 500 psi to 300 psi. On the basis of results obtained detailed investigation of spent sulfite liquor as a secondary additive with polystyrene stabilization is not recommended.

Reclaimed Rubber: The reclaimed rubber used in this study was obtained from Midwest Rubber Reclaiming Company. It was desolved in Creosote oil prior to addition to the soil. The solution consisted of 1 part reclaimed rubber and 3 parts Creosote oil. The percentages of reclaimed rubber and creosote oil added to the soil were 2, 4, 6 percent rubber and 6, 12, 18 percent creosote oil. A third combination tried consisted of 4.5 percent reclaimed rubber,13.5 percent Creosote oil and 4.5 percent spent sulfite liquor. None of the strengths obtained with these formulations gave satisfactory strengths; all dry strengths were about 100 psi and all immersed strengths were about

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[1]Roderick, G. L. and Demirel, T. Soil stabilization with polystyrene. Proc. Iowa Academy of Science, V. 71, pp. 369-376. 1964.

20 psi. On the basis of these results a detailed investigation of these additives is not recommended.

SOIL STABILIZATION WITH EPOXY RESIN

by

Lin Lu

and

T. Demirel

January 1966

INTRODUCTION

Soil stabilization may be broadly defined as any regulated process that alters or controls soil properties for the purpose of improving their engineering performance. Processes by which soils may be stabilized include the use of other soil, chemical additives, cement, compaction, moisture control, or combinations of these.

The major applications of soil stabilization are as follows:

1. Stabilized soil provides bases or surfaces for secondary and farm-to-market roads where good primary roads are already in existence.

2. Stabilized soil provides for high type pavements where high-type rock and crushed gravel normally employed for such bases are not economically available.

3. For military and other emergencies where an area must be made trafficable within a short period of time.

4. For economic development, stabilized soil roads can lift underdeveloped areas out of the mud.

5. For city and suburban streets where the noise absorbing and elastic properties of certain stabilized soil systems process definite advantages over other construction materials.

Up to now, there has been no entirely successful method for stabilization of soils by the use of chemical admixtures. Although several materials are suitable under specific conditions or with particular soils, none have proved to be universally acceptable.

Portland cement is the most generally effective soil-stabilizing material. However, under certain conditions, especially where wide

temperature variation prevails, the cement treated soils have not always proven to be a durable admixture.

Many kinds of synthetic resins have been used for soil stabilization. Some of them have shown promising results. One of these synthetic resins, epoxy resin has never been tried as a stabilizing agent. Cured epoxy resin is an inert, tough solid. It can resist the penetration of water and the attacks of de-icing chemicals, oil gasoline and other materials commonly encountered on highways.

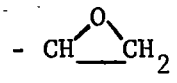
The objective of this research is to determine the effect of epoxy resin on soils which were treated by epoxy resin alone or epoxy resin with other additives. The other purpose is to give a tentative explanation of the mechanism of stabilization.

REVIEW OF LITERATURE

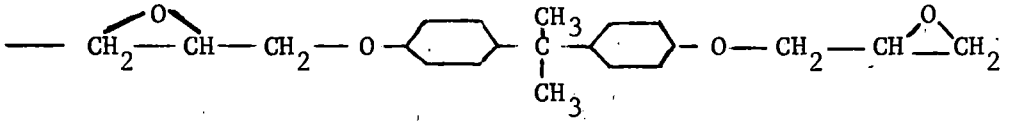
Epoxy Resin, Manufacturing Process and the Properties of its Polymers

The epoxy resin is one of the newest of the major industrial plastics. The resin cures into a thermosetting material which will retain its dimensional stability throughout its design range, i.e., they will not soften with heat or flow with pressure.

The epoxy-resin molecule is characterized by the reactive epoxy or ethoxyline groups (5)

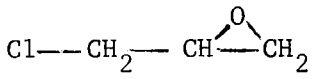


An unusually tough, extremely adhesive and highly inert solid results when crosslinking or cure is accomplished through these groups. The epoxy molecule is represented by the diglycidyl ether of bisphenol A (15).



The epoxy resins which have viscosities in the 8,000 to 20,000-centipoise range are predominately of this structure (15). The usual raw materials for the synthesis of the diglycidyl ether of bisphenol A are epichlorohydrin and bisphenol A.

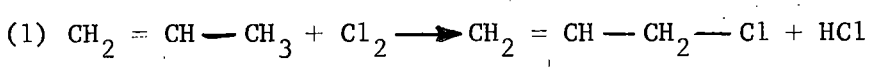
Epichlorohydrin is a colorless, mobil liquid having an irritating chloroform-like odor. It is represented by the formula:



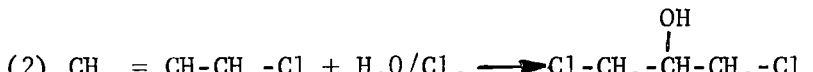
(15)

It is usually produced by the reaction of chlorine with propylene. The yielding allyl chloride is reacted with hypochlorous acid to produce dichlorohydrin which is exposed to sodium hydroxide at elevated temperature to strip off one hydrogen and one chlorine atom.

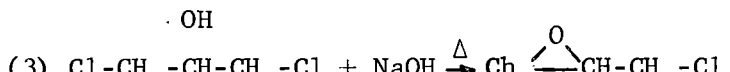
The three steps to yield epichlorohydrin from propylene can be expressed as follows:



Propylene Chlorine Allyl Chloride Hydrogen Chloric Acid

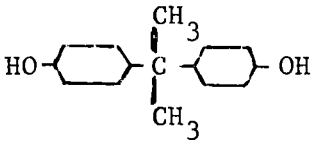


Allyl chloride water/chlorine Dichlorohydrin

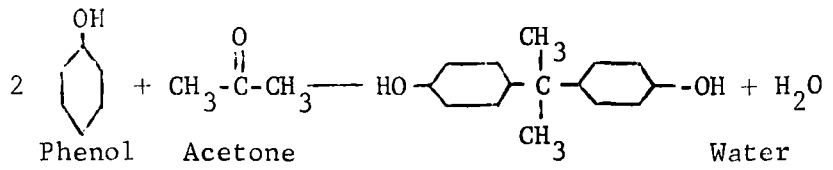


Dichlorohydrin Sodium hydroxide Epichlorohydrin

Bisphenol A or bis dimethyllnethane:

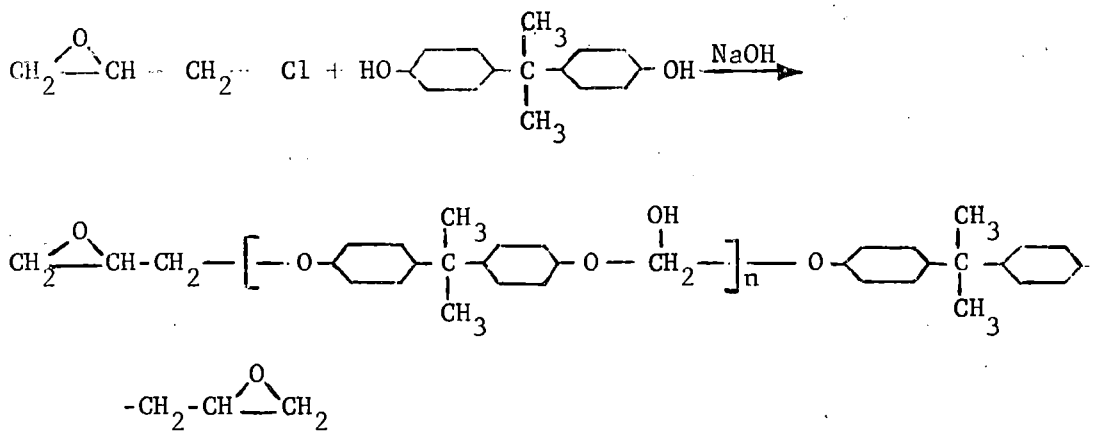


It requires two basic intermediates for synthesis: acetone and phenol (15):



Bisphenol A

Diglycidyl ether of bisphenol A is produced by reacting epichlorohydrin with bisphenol A in the presence of a caustic (5):



Where n is the number of repeated units in the resin chain; when n = 0 the molecular weight is 340; when n = 10, it is about 3,000.

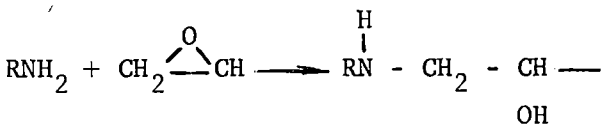
Epoxy resins in the pure or uncontaminated state possess indefinite shelf life. They are chemically stable at temperatures up to 200°C. The resins cure into thermoset compounds by three reactions (15): (1) direct linkage between epoxy groups; (2) linkage of epoxy groups with aromatic or aliphatic hydroxyls, and (3) cross-linkage with the curing agent through various radicals. Cured epoxy resins are very inert chemically. When the ether groups, the benzene rings and the aliphatic hydroxyls are present in the cured epoxy system, they are virtually invulnerable to caustic attack and extremely resistant to acids.

The epoxy resins which were used for this research were products of the Shell Chemical Company. They are furnished under the commercial names of Guardkote 120A and 120B. Guardkote 120A is composed of a diglycidyl ether of bisphenol A. 120B is a modified straight chain aliphatic amine containing both primary and secondary amine groups (18). The physical properties of the cured system are as follows (20):

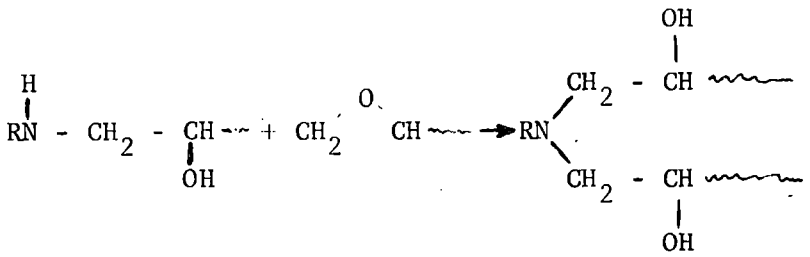
Tensile strength	4,900 psi
Tensile elongation	5%
Shore D hardness	77
Impact strength	0.6 ft - 16/in of notch
Flexural strength	8,600 psi
Flexural modulus	226,000 psi

The curing reactions possible with primary amines are (15):

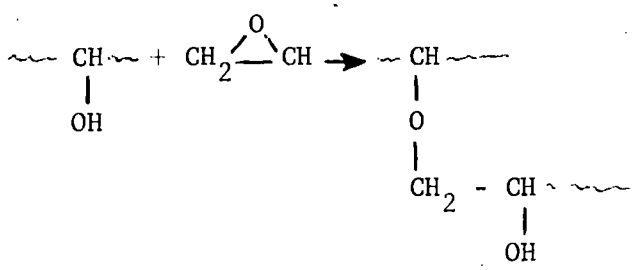
1. Reaction with an epoxy group to form a secondary amine



2. Another epoxy group is reacted to form tertiary amine



3. Reaction of hydroxyls so formed with epoxy



Review of Previous Work

Natural or synthetic resins which have been used for the purpose of soil stabilization may be divided into two groups: resinous waterproofing materials, and resinous waterproofing and bonding materials (16).

The chief function of resinous waterproofing materials is to maintain the moisture content of a soil at or below optimum moisture by preventing entry of water into the treated and compacted mixture. Very slight or no cementing action is obtained from the materials. Waterproofing agents usually attain maximum effectiveness when used in small quantities. Although imparting desirable characteristics to the soil, and providing considerable waterproofing effect under mild exposure, none of the water-repellent resins appears to be a suitable soil stabilizing agent at the present time. The most popular resinous waterproofing materials are Stabinol, Resin 321, Vinsol and NVX. Both Stabinol and Resin 321 were tested and reported by Mainfort (16) as soil stabilizing materials. Resin 321 in particular is the best waterproofing agent studied and its water-repellent characteristics can be utilized for improving the effectiveness of other stabilizing materials. In further studies by Mainfort (16), with more severe laboratory exposure and the use of a wide-range of soils, both stabinol and resin 321 were found to be ineffective under the more severe tests. Mainfort also indicated in his tests that Vinsol was superior to NVX but far inferior to both Stabinol and Resin 321.

Resin bonding materials, as used in soil stabilization, are con-

sidered to cement or bond the particles of soils with which they are mixed. The effectiveness of the resin treatment increases with the quantity used (16). This kind of treatment is still in experimental stages.

Mainfort (16) found aniline-furfural an effective bonding and waterproofing agent with the wide range of soils he used. Winterkorn (25) used aniline furfural as a soil stabilizer in his study for the Civil Aeronautics Administration. He found that the combination of either 70:30 or 35:65 parts by weight of aniline and furfural was a good resin binder. The 70:30 resin was the most effective of those tested for medium plastic soils with the small amounts of the chemicals used. The resin acted as both a binding agent and a waterproofing agent. But both combinations were found to be ineffective when used in alkaline mixes. Acid mixes resulted in maximum strengths.

Sheeler (19) used aniline furfural to stabilize Wisconsin loess with success. He found a ratio of 2 mol. aniline to 1 mol. of furfural produced the highest stability among the loess mixtures. The soil treated with aniline furfural was nearly dry after five days of air-curing and reached equilibrium after eight days regardless of the percentages of chemical content.

Hydrated lime has been tried as a catalyst to improve the strength of the loess soil. It was found that both immersed strength and dry strength were reduced by adding hydrated lime to the resin loess mixture. Either sodium hydroxide or aluminum chloride when added to the aniline-furfural-soil mixture resulted in increased strength. The immersed strength had a 28 percent increase by adding 0.3 percent aluminum

chloride to the mixture containing 5 percent aniline-furfural. He also found that the maximum strength occurred at 22 percent of 2 micron clay content. A maximum waterproofing at 3 percent resin content was obtained for loess soil; the moisture absorption increased with the increase of resin content. Aniline-furfural treated specimens were very resistant to freezing and thawing.

Mainfort (16) also found reresorcinol-formaldehyde to be the best synthetic resin for hardening soil under moist-cure conditions at room temperature. The treated soil showed considerable promise under severe laboratory exposure. Mainfort showed this synthetic resin is suitable for improving other more economical admixtures; particularly the bituminous materials. Synthetic resins such as phenol-formaldehyde resin, urea-formaldehyde resin polystyrene and furfural alcohol have also shown promise for use as soil stabilizers (16,18).

Epoxy resins have never been tried in the field of soil stabilization; it has been used for surfacing and repairing Portland cement concrete (20). Burns (6) used epoxy resin as an additive in asphaltic concrete. The epoxy-asphalt concrete paving mixtures were tested in a field test section under jet blast and fuel spillage to compare the effectiveness of an epoxy-asphalt binder tack coat with that of a conventional asphalt tack coat. It showed that epoxy-asphalt concrete properly designed and constructed would satisfactorily withstand jet blast temperatures in the order of 500^{o}F and is impervious to jet fuel. The epoxy asphalt binder tack coat resulted in a longer bond that the conventional asphalt tack coat.

MATERIALS USED

Soils

Four kinds of soils were used in this investigation; the choice of these soils depended on the amount of clay present. The soils were a friable Wisconsin age loess (Lab. No. 20-2), a plastic Wisconsin age loess (Lab. No. 528-4), a Kansan Gumbotil (Lab. No. 512-11) and a dune sand (Lab. No. S-6-2). All soils except the Kansan Gumbotil were grounded to pass a No. 10 sieve; while the Gumbotil soil passed the No. 4 sieve. The descriptions and properties of these soils are presented in Table 1.

Lime

The lime used in this study was a product of the U. S. Gypsum Co. It is a calcitic hydrated lime.

Epoxy Resin System

The epoxy system used in this research was a commercial product of the Shell Chemical Company. It is supplied under the name of Guardkote 120, in two components, Guardkote 120A and Guardkote 120B, which are individually stable. Guardkote 120A is an epoxy resin and Guardkote 120B is an amine hardener. The liquid Guardkote 120A can be cured at 80^{o}F to become an unusually tough solid by adding Guardkote 120B to it at a weight ratio of 5 parts 120A to 1 part 120B as suggested by

the producer (18). Hand mixing for three minutes is usually required and an exothermic chemical reaction starts after 25 minutes. Therefore, the pure epoxy system should be used within about 15 minutes.

Table 1. Description and properties of soils used

Sample	Friable Loess (Lab. No. 20-2)	Plastic Loess (Lab. No. 528-4)	Kansan Gumbotil (Lab. 512-11)	Dune Sand (Lab. No. S-6-2)
Textural composition, %				
Gravel (>2.0 mm)	0	0	0	0
Sand (2.0-0.074 mm)	0.4	0.2	0.9	94
Silt (0.074-0.005 mm)	80.0	60.8	56.7	4
Clay (<0.005 mm)	19.6	39.0	42.4	2
Clay (<0.002 mm)	16.0	33.0	----	--
Predominant clay mineral	Montmorillonite	"	"	--
Physical properties				
Liquid limit, %	30.8	52.1	49.4	--
Plastic limit, %	24.6	20.0	25.9	--
Plasticity index	6.2	32.1	23.5	Non-plastic
Shrinkage limit, %	22.3	----	----	
Chemical properties				
Cat. ex. cap., m.e./100g	13.4	23.5	----	--
Carbonates, %	10.2	1.5	----	Non-calcereous
pH	8.7	5.6	----	--
Organic matter, %	0.2	0.2	----	--
Classification				
Textural	Silty Loam	Silty Clay	Silty Clay	Fine Sand
Engineering (AASHO)	A-4 (8)	A-7-6 (18)	A-7 (15)	A-3 (0)

METHOD OF PROCEDURE

Preparation of Specimen - Phase 1

The first phase of the investigation includes the molding of miniature soil specimens 1 inch high by 1/2 inch diameter. These specimens required much less preparation time, soil and epoxy than would be required if larger specimens were used. The results obtained for the different epoxy resin contents should show the relative effectiveness of epoxy-soil combinations.

Since significant amounts of water would probably tend to interfere with amine-epoxy reaction, it was decided that only dry soils should be used. However, the mixture was too dry to make a uniform mixture without adding extra water. Two ways of preparing the epoxy resin solution were tried. In the first method Guardkote 120A and 120B were dispersed in water individually by adding a dispersing agent with each. Sodium-montmorillonite was found to be the best dispersing agent for the epoxy-water suspension. The required epoxy and hardener were obtained from their respective suspensions. It was necessary to add additional distilled water to the soil-epoxy-mixture to insure uniform mixing.

In the second method, the epoxy and hardener were prepared by mixing without preemulsification. The mixture was hand-mixed three minutes before using.

Mixing

Soils passing the #10 sieve were used in this investigation.

About 40 grams of soil were placed in a porcelain dish and the required amount of resin mixture was added to give the desired percentages of resin. The soil and the resin mixture were then mixed with a spatula. Water was added during mixing to increase the volatile content to the estimated optimum. Different mixing orders, Table 2, showed that the immersed strengths were affected by the order of mixing.

Molding

Three 1 inch by 1/2 inch specimens were molded from each mixture. The required amount of the mixture to produce a 1 inch by 1/2 inch specimen having a specified dry density was placed in a cylindrical mold and compacted with static pressure. The molding apparatus was the same used and described by Roderick (18). Specimens with 9, 11, 13, 15 and 17 percent epoxy resin were molded for each mixture with the friable loess. Specimens with 5 percent resin but different volatile contents were molded for each mixture with dune sand.

Curing

All specimens of 1 inch by 1/2 inch were cured at room temperature for seven days. Each was completely immersed in distilled water for a 24 hour period before testing. The unconfined compressive strength of a certain mixture was obtained from the average of three specimens.

Testing

The miniature specimens were tested by a proving ring type hand-operated testing machine. Its maximum capacity for 1 inch by 1/2 inch specimens was 600 psi. Any specimens for which the unconfined compressive strength was higher than 600 psi were tested by another higher capacity proving ring machine. The load at which the specimen failed was divided by the cross-sectional area of the specimen to give the unconfined compressive strength of the specimen.

Preparation of Specimen - Phase 2

The epoxy resin mixture which was used in this phase was one part Guardkote 120A and 0.4 part 120B by weight. The epoxy mixture was prepared by the second method explained in the description of methods for the first phase of this study.

Mixing

The amount of the prepared epoxy solution required to give the desired amount of epoxy content was added to the soil. The following mixing procedure which was used for it was found to be the best in getting higher immersed strengths in phase 1 investigation (Table 2):

A. The soil and the required amount of lime were mixed with a spatula for one minute (in case the second additive was used).

B. The required amount of distilled water was added to the soil or soil time mixture. It was then mechanically-mixed with a

Hobart Model C-100 mixer at low speed for one minute.

C. It was then hand-mixed for one-half minute to assure proper distribution and pulverization of the soil.

D. The epoxy-hardener mixture, which had been prepared by mixing thoroughly, was added to the soil, and the mixture was mixed by a Hobart mixer one and one-half minutes.

E. The mixture was then hand-mixed for one minute.

The above procedure of mixing was used to prepare all specimens for the rest of this investigation.

Molding

Immediately after mixing, three specimens 2 inches in diameter by 2 inches high were molded with a drop-hammer apparatus developed by Davidson and Chu (8). The apparatus is shown in Figure 1. A predetermined quantity of soil-chemical-water mixture was placed in the cylindrical mold and the mixture was compacted by dropping a five pound hammer through a distance of one foot. After compacting the first blow, the temporary support was removed and four additional blows were given to the specimen. The reverse side of the specimen was given five blows in the same way. Specimens were removed from the mold by means of a hydraulic jack. They were then weighed to the nearest 0.1 gram and their heights measured to the nearest 0.001 inch. The height of all specimens were maintained at 2.000 ± 0.050 inches. Representative moisture samples were taken from the mixing bowl just prior to molding the first specimen and immediately after molding the third.

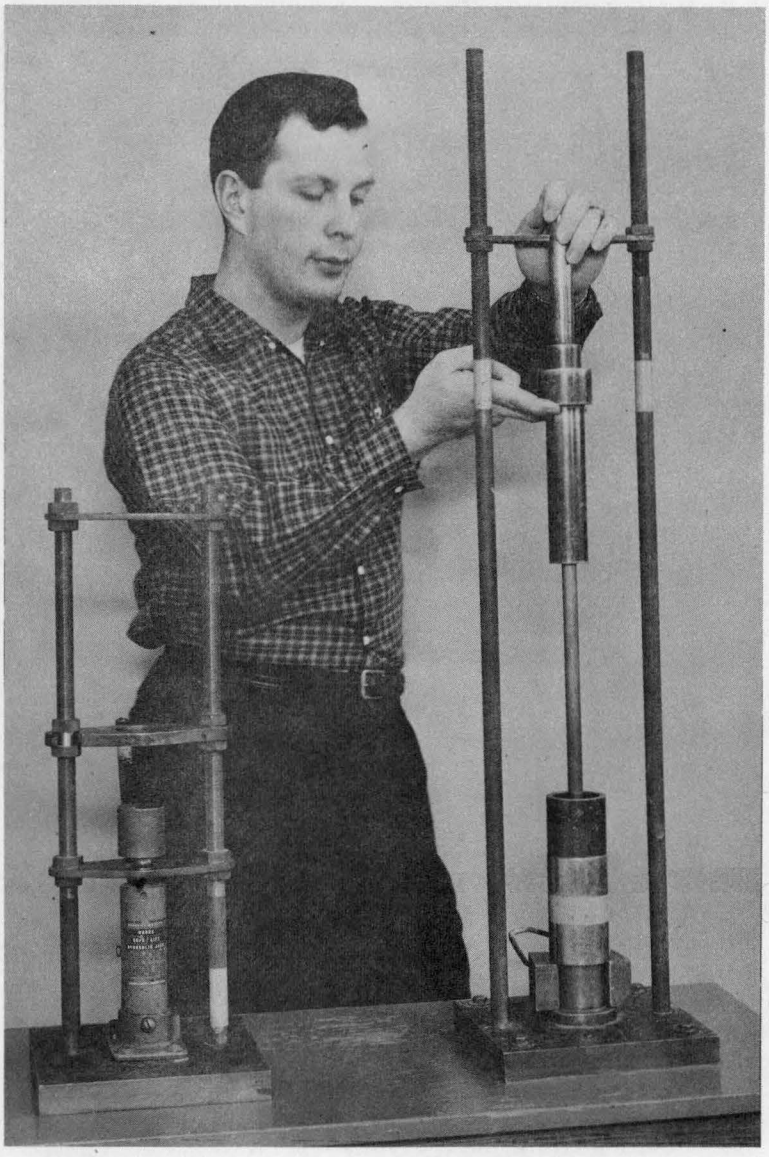


Figure 1. Apparatus for molding 2-inch diameter by 2-inch high test specimens. Drop hammer and molding cylinder shown in place.

The moisture samples were weighed to the nearest 0.01 gram, placed in an oven at 110°C for at least 16 hours and then weighed again. The moisture content for each mixture was determined to the nearest 0.1 percent on the basis of oven-dry weight of soil.

Curing

The specimens, prepared as above, were cured by air drying for various lengths of time at various temperatures. After curing, heights and weights were measured again. The specimens were then completely immersed in distilled water for a period of 24 hours. They were then weighed and measured again, and tested for unconfined compressive strength.

Testing

Unconfined Compressive Strength

The unconfined compressive strength was determined by the apparatus shown in Figure 2. Load was applied to the specimen at a deformation rate of 0.1 inch per minute until complete failure was attained. The maximum load in pounds divided by the cross-sectional area of the specimen was recorded as the unconfined compressive strength. The unconfined compressive strength obtained from specimens which were all immersed in distilled water for 24 hours after dry curing will be referred to as "immersed strength".

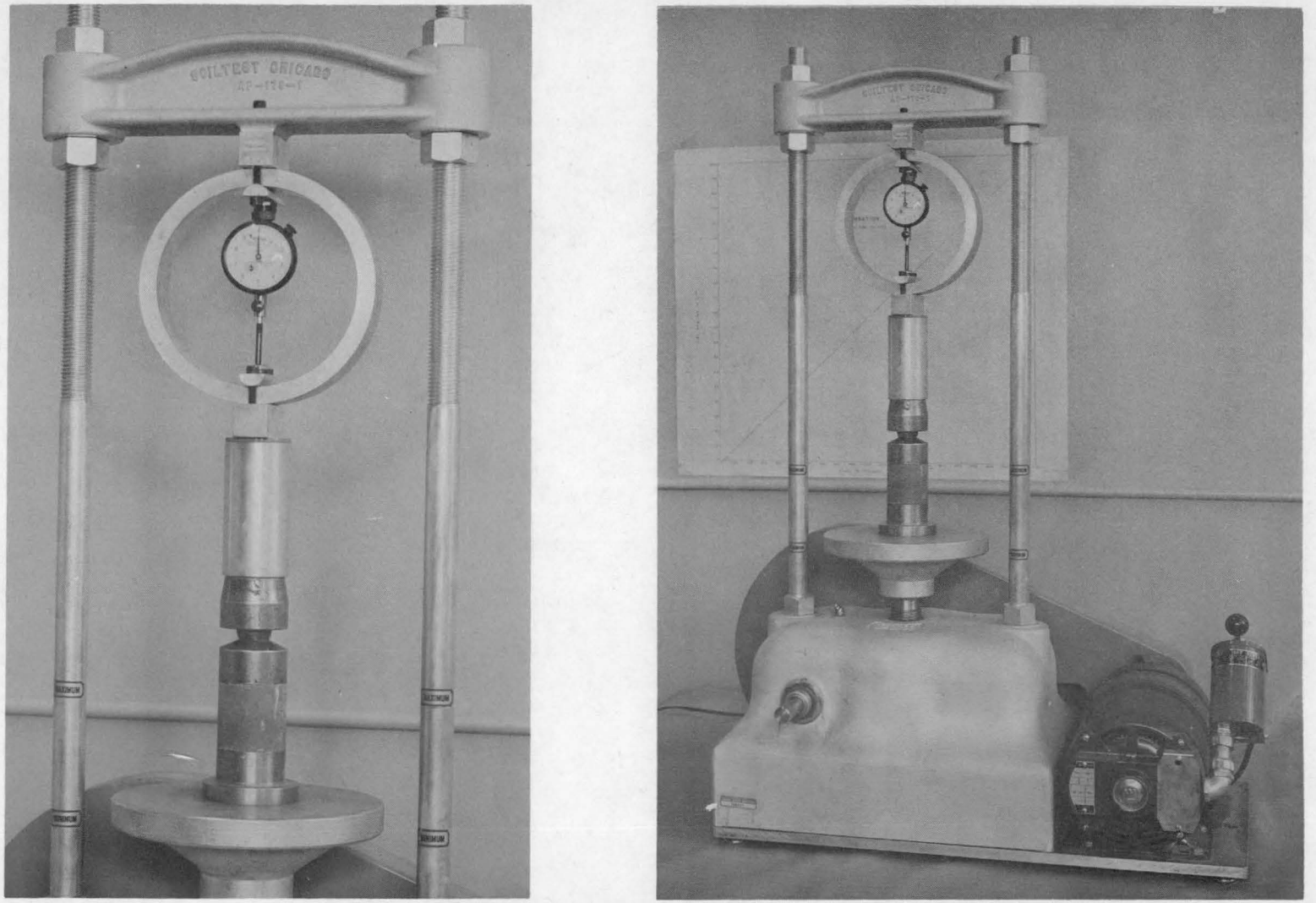


Figure 2. Two-inch diameter by 2-inch high specimen being tested for unconfined compressive strength.

Calculation of Dry Density

Dry density was calculated from the weight, height and volatile content determined at the time of molding.

$$\text{Dry density (pcf)} = \frac{\text{Wt. of specimen (gram)}}{\text{ht of specimen (inch)}} \times \frac{1.213}{1 + \frac{\text{volatile content (\%)}}{100}}$$

Calculation of Linear Shrinkage

Linear shrinkage was obtained after curing. It was calculated by comparison of the initial height and the height after curing

$$\text{Linear shrinkage (\%)} = \frac{\text{ht. after molding - ht. after drying}}{\text{ht. after drying}} \times 100$$

Calculation of Volatile Retention

After curing, the percentage of volatile which was retained in the specimen was calculated by the following formula

$$\text{Volatile retention \%} = \frac{\text{Wt. after curing} - \frac{\text{Wt. after molding}}{1 + \frac{\text{volatile at molding (\%)}}{100}}}{\frac{\text{Wt. after molding}}{1 + \frac{\text{volatile at molding (\%)}}{100}}}$$

Calculation of Linear Expansion

Linear expansion was obtained by comparison of the height after immersion and the height after dry curing

$$\text{Linear expansion \%} = \frac{\text{ht. after immersion - ht. after dry curing}}{\text{ht. after dry during}} \times 100$$

Calculation of Water Absorption

The amount of water absorption was calculated by the weight after

immersion, weight after molding, and the volatile content after molding.

$$\text{Absorption (\%)} = \frac{\text{Wt. after immersion} - \dfrac{\text{Wt. after molding}}{1 + \dfrac{\text{Volatile at molding (\%)}}{100}}}{\dfrac{\text{Wt. after molding}}{1 + \dfrac{\text{Volatile at molding (\%)}}{100}}} \times 100$$

Freeze-thaw Test

The following soil-epoxy resin admixtures were used in the Iowa Freeze-thaw Test:

Soil 528-4, Soil 20-2, Soil 512-11: 7 percent Guardkote 120A + 2.8 percent 120B + 2 percent calcitic hydrated lime

Soil S-6-2; 3 percent Guardkote 120A + 1.2 percent 120B + 2 percent calcitic hydrated lime.

Four specimens of 2 inch high by 2 inch diameter were molded at the optimum volatile content for maximum immersed strength for each of the above soil-additive mixes. The specimens were cured by drying 24 hours in a 104°F (40°C) oven. After curing they were tested by the Freeze-thaw test developed at the Iowa Engineering Experiment Station (12). Two specimens prepared from the same batch were completely immersed in distilled water for a period of 11 days. The remainder were given one day immersion and then followed by ten cycles of freezing and thawing. One freeze-thaw cycle consisted of 16 hours freezing at 20 ± 2°F and 8 hours thawing at room temperature. Sufficient water at a temperature of 35°F was maintained in the vacuum flask so that the specimen would contact water. At the completion of freeze thaw cycles and immersion,

all specimens were weighed, and their heights measured; the specimens were then tested for unconfined compressive strength.

Two specimens were molded from each of the raw soils at their optimum moistures. They were cured by drying at room temperature for seven days and were then subjected to several cycles of the freeze-thaw test. The specimens were not immersed in water because they would have slaked. The amount of expansion of those untreated specimens were compared with that of the resin treated specimens. Figure 14 shows the relative heaves of the treated and untreated specimens.

PRESENTATION AND DISCUSSION OF RESULTS - PHASE 1

The screening test is used to find what chemicals can be used to stabilize soil and what kinds of catalysts are feasible for the chemicals used in the laboratory test. Since the screening test specimens utilized less material and time than 2 inch by 2 inch specimens would require, the screening test is preferable when the effects of chemicals used as a stabilizing agent is not known. However, the immersed strength obtained from the screening tests were not always reproducible. The relationship of strength to percent chemicals added was not clearly defined by this kind of test. For this reason only friable loess (20-2) and dune sand (S-6-2) soils were investigated in phase 1 of the experiment.

Specimens containing 9, 11, 13, 15 and 17 percent epoxy were molded with friable loess (20-2). Epoxies pre-emulsified by using sodium montmorillonite as a dispersing agent were used. The results obtained from different combinations are presented in Table 2.

Since the specimens with pre-emulsified epoxy and hardener did not show higher immersed strengths than those with only mixed epoxies it was concluded that premulsification of epoxy and hardener was not necessary. The results showed that higher immersed strength would be obtained if the ratio for epoxy and hardener was 1 to 0.4 rather than 1 to 0.2. It was found that the extra water did not impede the adhesion between resin and clayey soil. On the contrary, a certain amount of water improved the interaction between the resin and soil. An optimum molding volatile content for immersed strength could be

Table 2. Effect of various epoxy resin contents on immersed strengths for friable loess and dune sand miniature specimens.

Soil	Epoxy 120A %	120B %	Molding Volatile Content %	Na Mont. %	Method of curing	Method of Mixing	Average immersed strength psi A	B
20-2	9	3.6	17.0	1.0	A = 7 days of room temperature and 24 hours in immersed water	I	34	40
	11	4.4	20.5	1.0		I	77	98
	13	5.2	17.7	1.5		I	295	885
	15	6.0	18.3	2.0	B = 14 days at room temperature and 24 hours in immersed water.	I	394	545
	17	6.8	18.0	2.0		I	1325	1780
	17	6.8	16.5	2.0		I	2243	2243
	11	2.2	18.0	0			168	
	11	4.4	18.0	0		I	320	
	13	5.2	18.0	0	A	"	746	
	15	6.0	18.0	0		"	1140	
	17	6.8	18.0	0		"	1200	
	11	4.4	13.4	0		I	219	
	11	"	15.4	"		"	877	
	11	"	17.4	"	A	"	780	
	11	"	19.4	"		"	373	
	11	"	21.4	"		"	176	

Table 2
Cont.

Soil	Epoxy 120A %	120B %	Molding Volatile Content %	Na Mont. %	Method of Curing	Method of Mixing	Average immersed Strength, psi
20-2	17	6.8	18.0	0	A	II	746
	17	6.8	18.0	0	"	III	1711
	17	6.8	18.0	0	"	IV	1667
S-6-2	5	2.0	10	0	A	I	346
	5	2.0	0	0	"	I	266
	5	2.0	10	0	"	II	63
	5	2.0	10	0	"	III	346

Methods of Mixing

I. Extra water was added to soil at the same time with the prepared epoxy.

II. Extra water was added after the soil and the prepared epoxy had been mixed.

III. Extra water was added and mixed with soil; the prepared epoxy was then added and mixed.

IV. Extra water was added to the prepared epoxy; the mixture was then mixed with the soil.

found in the combinations of the same epoxy content with different percentages of volatiles at molding. Four different mixing orders were tried for 20-2 soil and the one in which extra water was added before the soil and the prepared epoxy had been mixed (mixing order III) proved the best in getting higher immersed strength.

Specimens containing only 5 percent epoxy with different mixing orders were prepared with soil S-6-2. Different mixing orders for the sandy soil also made the specimens fail at different immersed strengths. If the water and epoxy were added to the sandy soil at the same time or water was added to the sandy soil at the same time before adding of epoxy mixture, the immersed strengths would be higher than that of the specimens made by the mixing order II, (see Table 2). The conclusion is that the mixing water should never be added into the mixture after the epoxy and sand had been mixed. If water and epoxy were added to the sandy soil at the same time or sand was mixed with water first then the mixture was mixed with epoxy, the water might enable the epoxy to be more uniformly distributed. If the water were added after mixing the soil with epoxy only, the epoxy was unevenly distributed in the soil mass and it resulted in poor immersed strength.

The erratic results of this phase of the study were probably due to the dimensional effect of the miniature specimens. It was however, concluded that: (1) pre-emulsification of epoxy system was not necessary to incorporate the resin with wet soils; (2) water did not impede the adhesion between resin and soil, on the contrary a certain amount of water improved the resin-soil interaction and (3) the third mixing order (see Table 2) was best in getting higher immersed strength. Thus, this phase of the study laid the course for phase 2 study.

PRESENTATION AND DISCUSSION OF RESULTS - PHASE 2

Effect of Epoxies on Optimum Volatiles on Immersed Strength and Dry Density

The percentages of epoxy added to the friable loess, based on dry weight of the soil were 7, 9, 11, and 13 percent in this investigation. Further tests were conducted by adding two percent lime to the friable loess-epoxy specimen containing 5, 7, and 9 percent epoxy. Tests were run for plastic loess and gumbotil soils. The mixtures of both soils contained 5, 7, and 9 percent epoxy and 2 percent lime. Two percent lime was also added to epoxy-sand mixtures which contained 2, 3, and 4 percent epoxy.

For each combination of those percentages, five or six sets of three specimens were prepared with different volatile contents. Each specimen of the same set was maintained within $\pm$ 1.0 percent in volatile content and $\pm$ 3 pcf in dry density according to ASTM Designation B 560-57 (1). Figure 3 shows the relationships of immersed strength versus days of dry curing for soil 20-2. With seven days dry curing at 80° F (room temperature) the maximum immersed strength for 7 percent resin content is 580 psi from Table 3. Tests showed that the immersed strength decreased with decreasing curing temperature.

It was found that the specimens of 20-2 soil with 7 percent epoxy content at optimum volatile content yielded the same immersed strength if they were cured in an oven at 104°F (40°C) for one day instead of seven days dry curing at room temperature. The oven curing not only

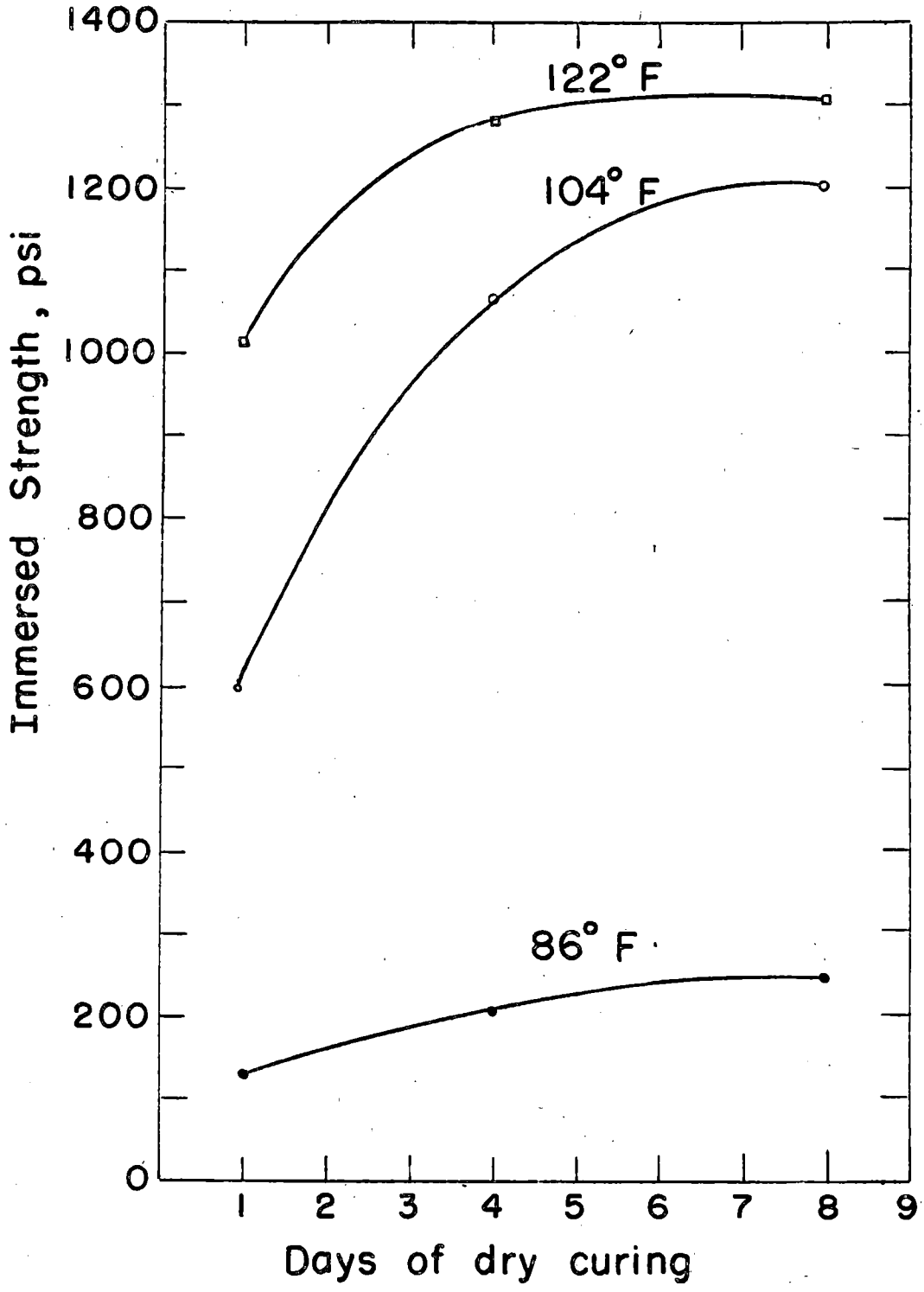


Figure 3. Effect of curing time on immersed strengths of epoxy resin-friable loess specimens.

shortens the curing time but also standardizes the curing temperature. All specimens with lime or other additives were cured under this condition.

All specimens were immersed in distilled water for 24 hours prior to testing for unconfined compressive strength. The strength of the individual specimens was maintained within 10 percent of the average value as required by ASTM Designation C109-54 (2).

The dry densities and immersed strengths obtained for different compositions are presented in Tables 3, 4, 5, and 6. The relationships between immersed strengths and molding volatile contents are shown in Figure 4, 5, 6, and 7. The dry densities versus molding volatile contents are shown in Figures 11, 12, and 13. From these density-volatile and immersed strength-volatile relationships the optimum molding volatile content for density and for strength were obtained and are tabulated in Tables 3, 4, 5, and 6.

Both Figures 4 and 5 show that the immersed strength of the friable loess increases with increasing epoxy content. The immersed strength gain from 7 percent to 9 percent epoxy content is 400 psi. However, if 2 percent of lime were added to the mixtures, the maximum strength gain would be approximately 850 psi. The epoxy-soil mixture yielded much greater immersed strength if 2 percent lime were added. The optimum molding volatile content for maximum immersed strength of epoxy-friable loess mixtures decreased 1.5 percent with every increase of 2 percent epoxy content from 7 percent epoxy content up to 13 percent epoxy content. For epoxy-lime-friable loess mixtures, the optimum volatile content for strength is seen to be nearly the

Table 3. Effect of Guardkote 120A and 120B on the properties of the friable loess (Lab. No. 20-2).

Guardkote 120 A %	120 B %	Molding Volatile Content %	Average Dry Density %	Optimum Volatiles for Density %	Maximum Dry Density pcf	Individual Immersed Strength psi			Average Immersed Strength psi	Optimum Volatile Content for Strength %	Maximum Immersed Strength psi	Average Linear Shrinkage	Average Volatile Retention %	Average Linear Expansion on Immersion, %	Average Moistures Absorption on Immersion, %
7	2.8	9.29	100.10			481	550	494	508			-0.13	2.1	-0.05	14.20
7	2.8	11.24	99.43			517	475	468	487			-0.12	3.0	-0.03	16.40
7	2.8	13.23	100.66			517	461	491	496			-0.17	3.3	0.00	15.15
7	2.8	14.17	101.54			554	593	563	570			-0.10	1.24	+0.25	10.48
7	2.8	14.21	100.18			485	524	718	576			-0.28	4.4	+0.39	14.12
7	2.8	14.96	100.55			606	633	517	586			-0.05	3.4	-0.06	11.66
7	2.8	19.93	97.91	15.00	100.10	356	366		361	14.00	580	+0.42	4.3	+0.15	17.84
9	3.6	7.85	98.77			639	633	596	623			+0.1	2.9	+0.31	18.00
9	3.6	9.52	100.77			833	850	814	832			+0.15	3.0	+0.30	15.22
9	3.6	12.21	102.00			993	896		945			+0.25	3.5	-0.05	9.23
9	3.6	14.90	102.15			590	656	1,011	752			-0.22	4.4	-0.07	10.89
9	3.6	15.82	102.40			465	478	774	572			+0.45	4.0	+0.03	13.28
9	3.6	18.15	99.66	14.50	102.50	567	567	685	606	12.50	1,000	+0.37	3.9	+0.07	11.52
11	4.4	5.05	99.58			814	929	902	882			-0.05	2.9	+0.48	13.53
11	4.4	6.93	100.30			994	863	797	885			+0.24	3.6	+0.39	16.36
11	4.4	8.70	102.40			922	1,126	1,116	1,055			+0.20	3.7	+0.26	10.40
11	4.4	12.10	101.70			1,153	1,093	1,086	1,110			-0.20	5.8	+0.19	11.10
11	4.4	14.45	103.87			823	837	892	851			+0.06	7.7	+0.25	13.39
11	4.4	15.18	103.32			748	837	1,017	867			+0.53	6.6	+0.05	12.32
11	4.4	18.00	98.71	13.50	104.0	445	475	649	523	10.50	1,135	+0.70	7.9	-0.20	15.04
13	5.2	5.66	103.87			1,120	1,289	955	1,121			+0.05	4.4	0.00	12.32
13	5.2	9.20	104.66			1,619	1,027	1,751	1,466			+0.40	6.7	+0.32	12.05
13	5.2	11.51	105.00			1,040	1,208	1,090	1,113			+0.89	8.7	+0.18	10.37
13	5.2	13.39	104.17			1,106	1,093	1,225	1,141			+0.47	9.2	0.00	12.42
13	5.2	13.72	103.34	10.50	105.2	781	856	948	862	9.00	1,490	+1.08	7.3	+0.02	11.96

Table 4. Effect of Guardkote 120A, 120B and lime on the properties of the friable loess (Lab. No. 20-2).

Lime %	120 A %	120 B %	Molding Volatile Content %	Average Dry Density pcf	Optimum Volatile for Density %	Maximum Dry Density pcf	Individual Immersed Strength psi		Average Immersed Strength psi	Optimum Volatile Content for Strength	Maximum Immersed Strength psi	Average Linear Shrinkage %	Average Volatile Retention %	Average Linear Expansion on Immersion, %	Average Moisture Absorption on Immersion, %
2	5	2.0	11.88	100.46			294	277	286			-0.60	1.8	+0.40	18.3
2	5	2.0	13.63	100.40			323	287	305			+0.40	2.2	+0.27	15.3
2	5	2.0	14.85	100.71			373	343	358			+0.10	2.8	+0.15	16.4
2	5	2.0	16.74	104.03	16.80	104.0	452	471	462	16.80	470	+0.40	4.4	+0.27	17.6
2	7	2.8	8.24	98.82			857	817	837			+0.45	1.8	+0.47	11.5
2	7	2.8	10.35	99.83			768	801	785			+0.43	2.6	+0.55	11.9
2	7	2.8	11.76	101.39			798	768	783			+0.35	2.7	+0.30	11.6
2	7	2.8	13.31	102.20			745	732	739			+0.17	5.0	+0.12	8.6
2	7	2.8	15.30	102.74			517	508	513			+0.12	7.5	-0.15	9.9
2	7	2.8	16.90	101.10	14.40	103.9	629	636	633	9.50	840	+1.30	4.8	+0.05	9.9
2	9	3.6	8.64	99.22			1,623	1,442	1,533			+0.50	2.7	+0.50	11.0
2	9	3.6	10.36	102.80			1,718	1,646	1,682			+0.33	3.7	+0.28	10.6
2	9	3.6	12.18	104.60			1,179	1,176	1,178			+0.15	6.0	+0.15	9.6
2	9	3.6	13.29	105.05			1,001	978	989			+0.13	7.3	-0.13	9.8
2	9	3.6	15.08	102.87	13.00	105.2	613	616	615	10.00	1,700	+0.90	8.7	0	13.0

Table 5. Effect of Guardkote 120A, 120B, and lime on the properties of the plastic loess (Lab. No. 528-4).

120 A %	120 B %	Lime %	Molding V. C. %	Average Dry Density pcf	Optimum Volatile for Density	Maximum Dry Density pcf	Individual Immersed Strength psi		Average Immersed Strength	Optimum Volatile Constant for Strength	Maximum Immersed Strength psi	Average Linear Shrinkage	Average Volatile Retention	Average Linear Expansion on Immersion,%	Average Moisture Absorption on Immersion, %
5	2.0	2.0	11.00	102.90			399	389	394			0.58	2.7	0.45	15.2
5	2.0	2.0	13.42	105.18			458	458	458			0.70	4.4	0.25	14.9
5	2.0	2.0	15.63	106.07			442	458	450			0.75	4.9	0.20	17.4
5	2.0	2.0	16.90	105.59			501	498	499			1.10	5.4	0.30	18.5
5	2.0	2.0	19.22	102.06	15.50	106.10	442	435	428	16.70	500	1.50	6.0	0.35	19.1
7	2.8	2.0	11.43	103.43			596	616	606			0.50	3.8	0.35	12.7
7	2.8	2.0	13.02	106.58			735	824	779			0.80	4.4	0.30	12.8
7	2.8	2.0	15.15	106.14			791	826	808			1.05	6.6	0.33	13.2
7	2.8	2.0	16.23	103.79			686	672	679			1.40	6.0	0.40	17.0
7	2.8	2.0	18.44	101.08	14.00	107.40	504	609	537	14.50	810	1.55	7.9	0.25	17.7
9	3.6	2.0	10.61	102.83			1,040	929	985			0.50	4.2	0.50	16.6
9	3.6	2.0	11.81	105.55			965	1,008	987			0.90	5.0	0.40	14.1
9	3.6	2.0	13.88	106.98			1,021	998	1,050			0.95	7.5	0.35	13.8
9	3.6	2.0	15.40	104.04	13.50	107.85	972	952	962	13.00	1,020	1.24	7.7	0.40	14.4

Table 6. Effect of Guardkote 120A, 120B and lime on the properties of the Kansan Gumbotil (Lab. No. 512-11)

120A %	120B %	Lime %	Molding Volatile Content %	Average Dry Density pcf	Optimum Volatile For Density %	Maximum Dry Density pcf	Individual Immersed Strength psi		Average Immersed Strength psi	Optimum Volatile Content For Strength	Maximum Immersed Strength psi	Average Linear Shrinkage	Average Volatile Retention	Average Linear Expansion On Immersion	Average Moisture Assumption On Immersion,%
5	2.0	2.0	12.81	97.55			241	248	245	20.0	429	0.60	2.6	0.70	20.7
5	2.0	2.0	14.51	100.22			264	251	258			0.65	3.6	0.65	20.0
5	2.0	2.0	16.90	100.90			277	300	289			0.70	3.7	0.55	20.4
5	2.0	2.0	18.20	99.82			356	290	323			1.20	3.7	0.50	19.4
5	2.0	2.0	20.06	98.09	16.40	101.00	471	386	429			1.45	4.2	0.50	20.0
7	2.8	2.0	14.18	95.60			501	458	479	18.0	600	0.75	4.3	0.55	18.5
7	2.8	2.0	15.76	98.26			471	524	498			0.60	4.6	0.25	20.0
7	2.8	2.0	17.90	99.36			642	554	598			0.85	5.9	0.40	19.1
7	2.8	2.0	19.11	98.00			461	465	463			1.15	6.5	0.35	19.8
7	2.8	2.0	22.90	94.33	17.40	99.60	491	501	496			2.05	7.3	0.25	21.4
9	3.6	2.0	14.67	98.44	16.5	101.85	846	732	789	17.0	850	1.10	3.9	0.80	19.3
9	3.6	2.0	16.35	101.74			853	791	822			1.40	4.4	0.75	17.2
9	3.6	2.0	17.93	99.05			846	824	835			1.15	4.9	0.65	17.7
9	3.6	2.0	19.32	97.28			682	577	630			1.50	6.6	0.55	18.9

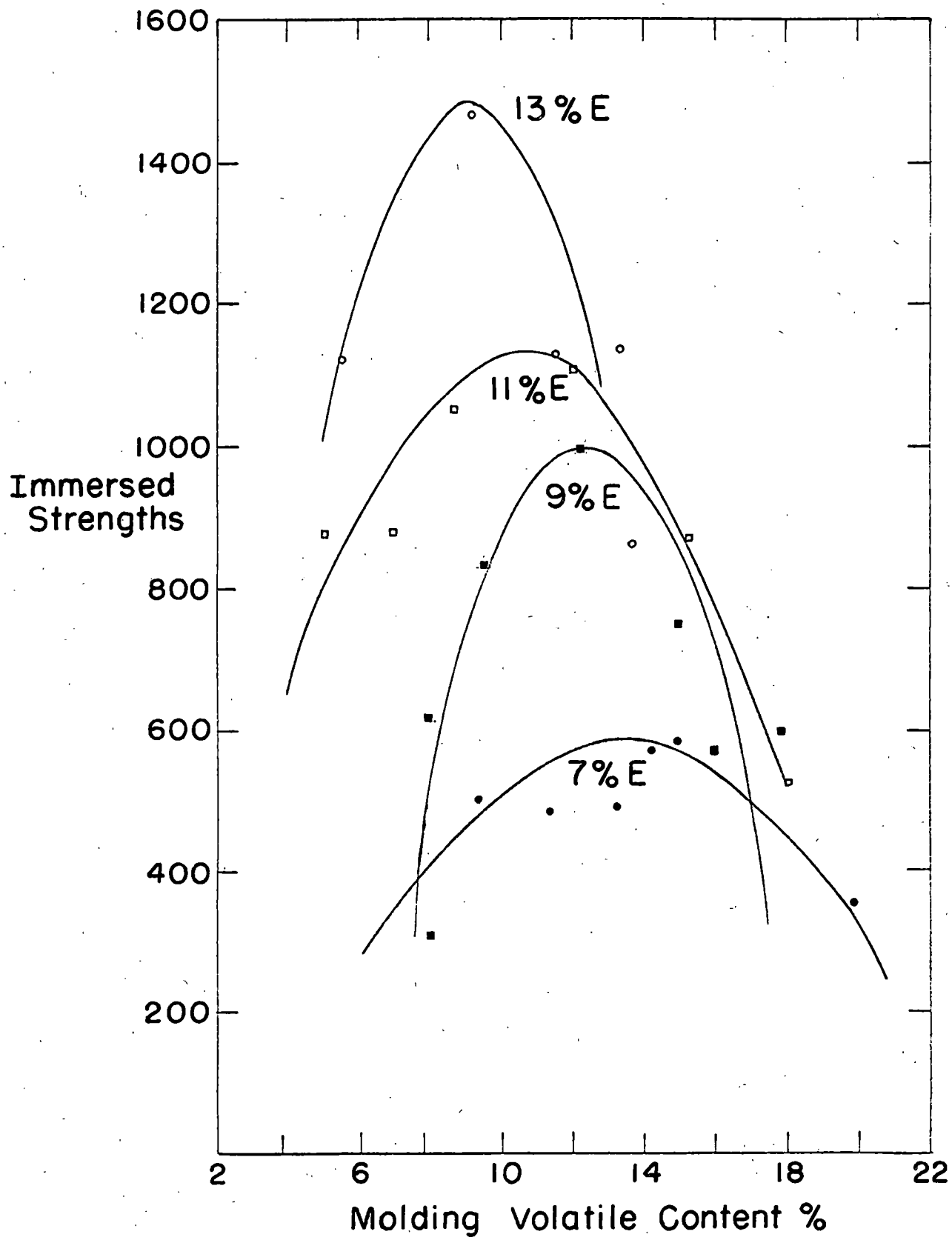


Figure 4. Molding volatile content -- immersed strength relationship for epoxy resin-friable loess mixtures.

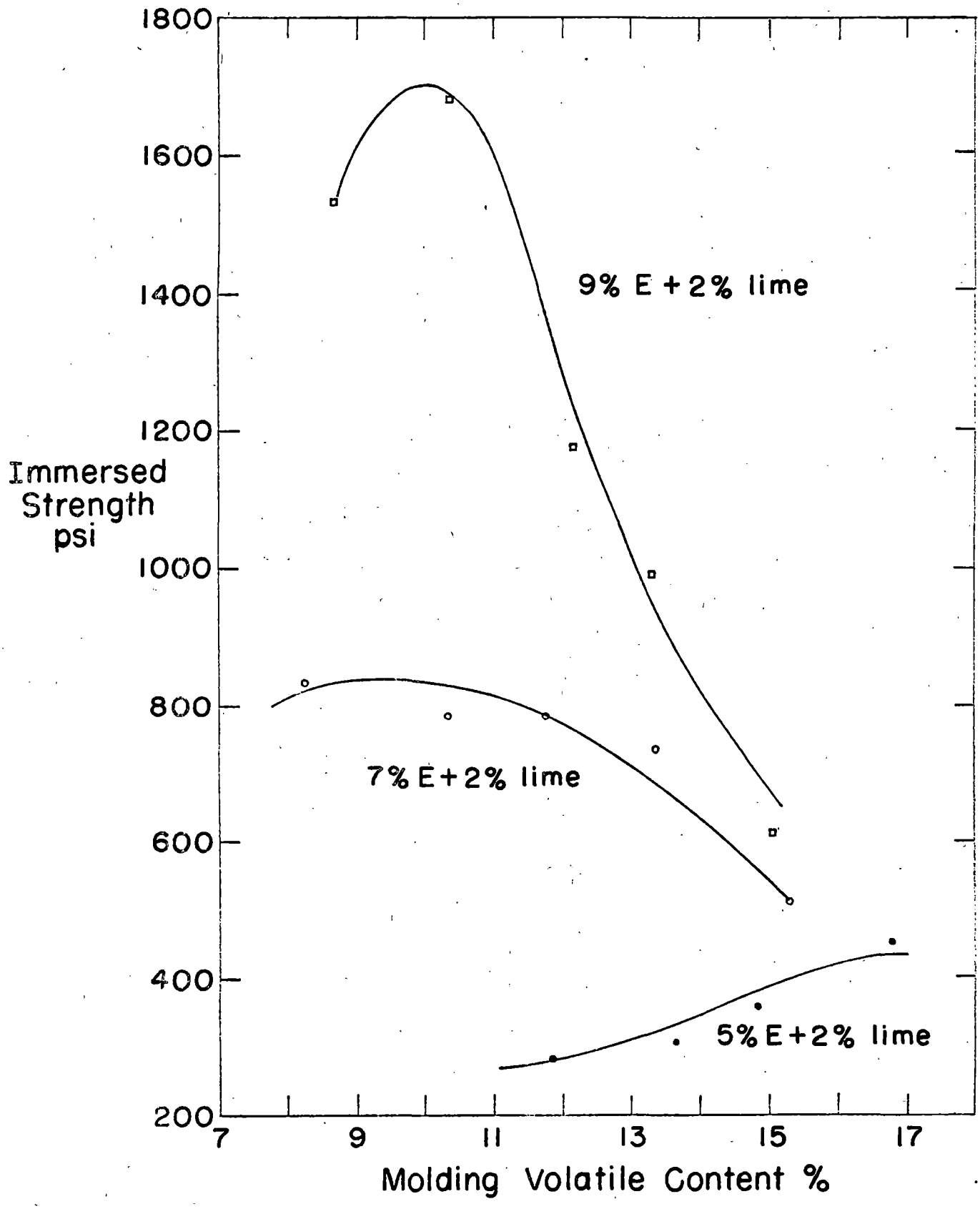


Figure 5. Molding volatile content -- immersed strength relationship for epoxy resin-lime-friable loess mixtures.

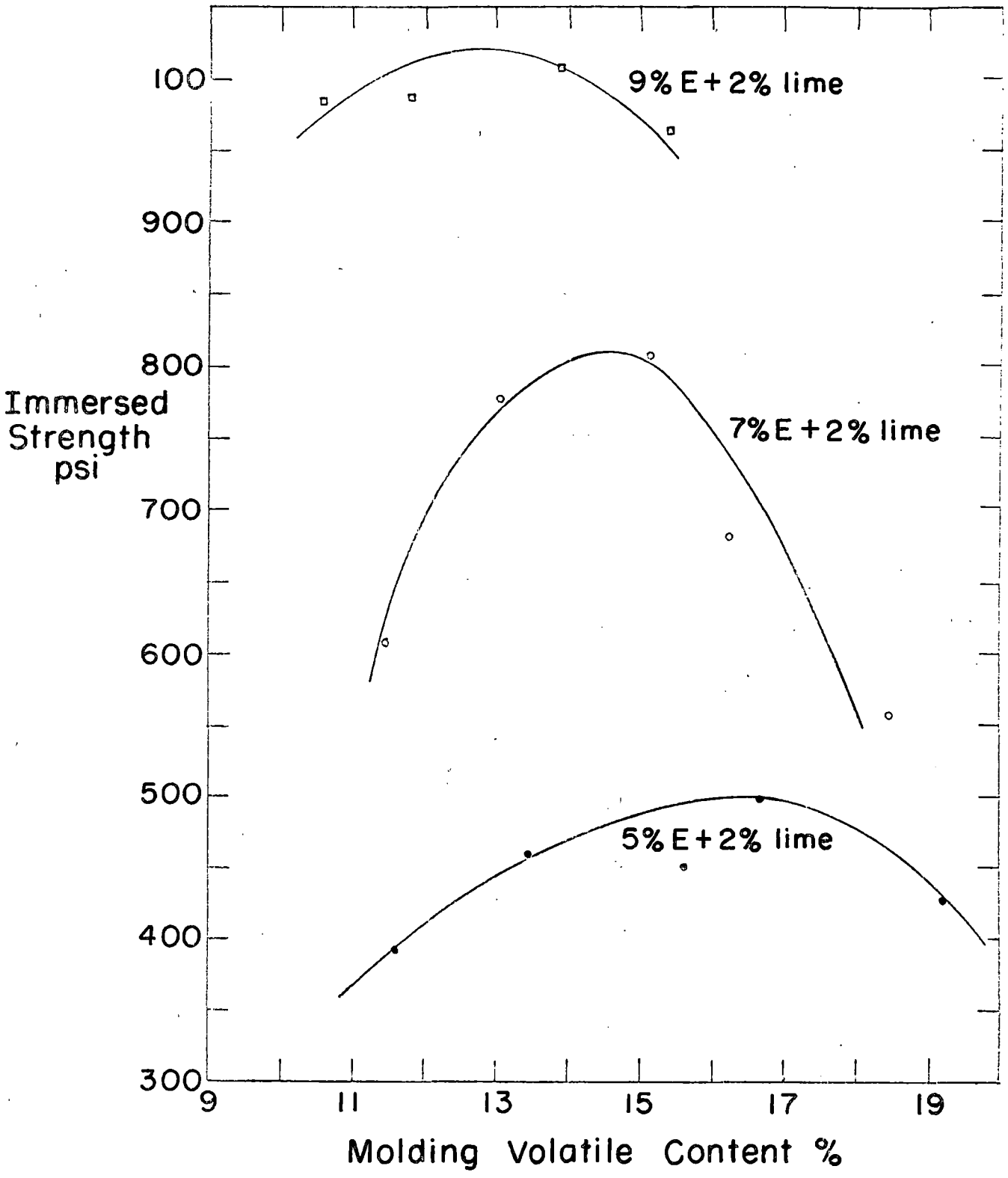


Figure 6. Molding volatile content -- immersed strength relationship for epoxy-lime-plastic loess mixtures.

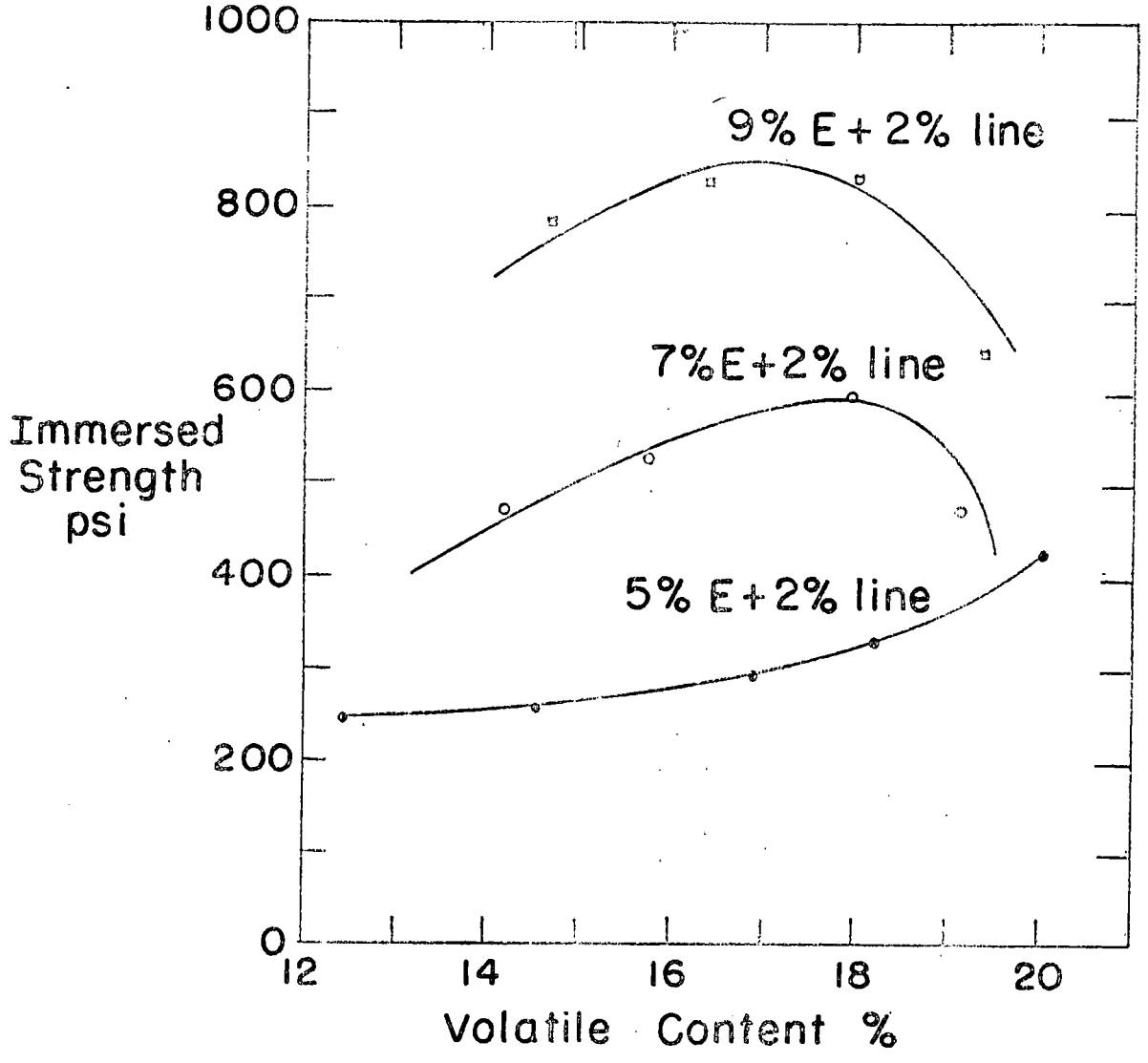


Figure 7. Molding volatile content -- immersed strength relationship for epoxy-lime-gumbotil mixtures.

same for 7 and 9 percent of epoxy content.

Figures 6 and 7 for plastic loess and gumbotil show the same pattern as that for friable loess, but when the epoxy content was increased to 9 percent the rate of strength change with increasing volatile content was less. At volatile contents higher than 20 percent the specimen would have many slickensides after compaction, so no more satisfactory specimens could be obtained. The plastic loess contained 39 percent clay and the gumbotil had 42.4 percent clay; both had higher clay contents than the friable loess, which had 19.6 percent. With 9 percent epoxy and 2 percent lime, the maximum immersed strength of the plastic loess and gumbotil specimens were 60 percent and 50 percent, respectively, of the maximum immersed strength of the friable loess specimens. Apparently, soils with heavy clay content are less effectively stabilized with epoxy-lime than other soils with less clay content.

Other additives, therefore, were tried to improve the stability of the epoxy-lime-gumbotil mixture. Table 7 and Figure 8 shows the strengths obtained with various chemicals, lime and cement. Lime still proved to be the best additive among all chemicals used in the epoxy-gumbotil mixture. Specimens with 2 percent lime and 5 percent epoxy had higher immersed strength than the specimens with 6 percent lime and 5 percent epoxy. With 4 percent lime, specimens showed higher immersed strength than the specimens with 2 percent lime after curing at $40^{\circ}C$ oven for seven days; however the strength difference of the two mixtures was not significant after curing for one day. The increase in strength after seven days is probably due to the increase of lime content. Therefore, 2 percent lime, based on dry soil weight, was

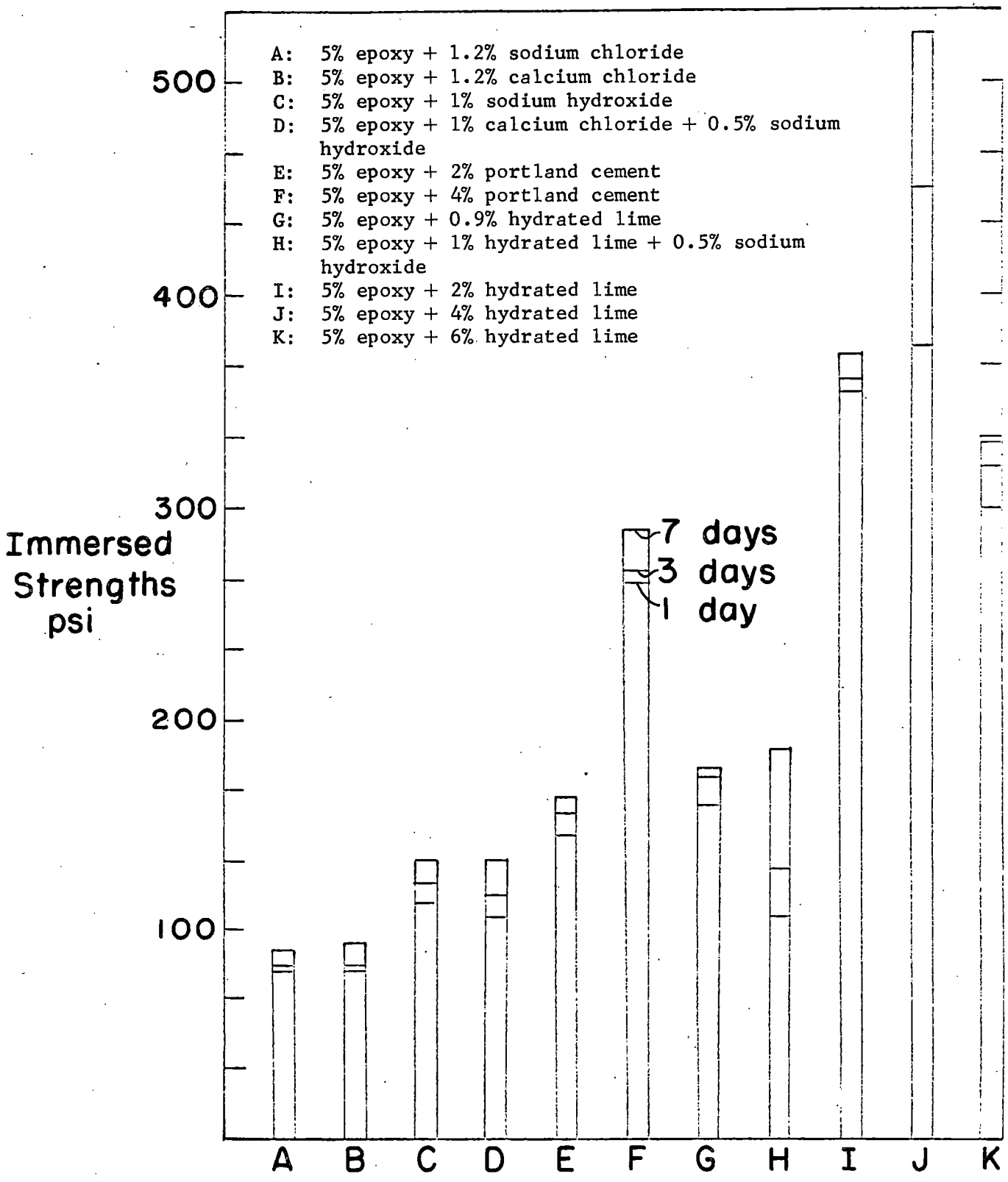


Figure 8. Effect of different additives on immersed strength of epoxy-gumbotil mixture.

Table 7. Effect of guardkote 120 A, 120 B and different additives on the immersed strengths of the Kansan gumbotil (Lab. No, 512-11)

120 A %	120 B %	V. C. %	Additives %	Curing Time	Ave. Strength psi
5	2.0	16.40	2% lime	one day	356
5	2.0	16.40	2% lime	three days	363
5	2.0	16.40	2% lime	seven days	373
5	2.0	17.36	4% lime	one day	376
5	2.0	17.36	4% lime	three days	452
5	2.0	17.36	4% lime	seven days	521
4%	1.6	17.84	6% lime	one day	297
4%	1.6	17.84	6% lime	three days	320
4%	1.6	17.84	6% lime	seven days	330
5%	2.0	16.00	1.2% NaCl	one day	80
5%	2.0	16.00	1.2% NaCl	three days	83
5%	2.0	16.00	1.2% NaCl	seven days	90
5%	2.0	16.00	1.2% $CaCl_2$	one day	80
5%	2.0	16.00	1.2% $CaCl_2$	three days	83
5%	2.0	16.00	1.2% $CaCl_2$	seven days	96
5%	2.0	16.00	1% NaOH	one day	113
5%	2.0	16.00	1% NaOH	three days	123
5%	2.0	16.00	1% NaOH	seven days	133
5%	2.0	16.00	1% $Ca(OH)_2$	one day	106
5%	2.0	16.00	0.5% Na(OH)	three days	116
5%	2.0	16.00	0.5% Na(OH)	seven days	133
5%	2.0	16.00	2% cement	one day	146
5%	2.0	16.00	2% cement	three days	156
5%	2.0	16.00	2% cement	seven days	162
5%	2.0	16.00	4% cement	one day	264
5%	2.0	16.00	4% cement	three days	271
5%	2.0	16.00	4% cement	seven days	290

Table 7 (continued)

120 A %	120 B %	V. C. %	Additive %	Curing Time	Ave. Strength psi
5%	2.0	18.00	0.9% lime	one day	159
5%	2.0	18.00	0.9% lime	three days	172
5%	2.0	18.00	0.9% lime	seven days	175
5%	2.0			one day	106
5%	2.0	16.00	2% lime and 0.5% NaOH	three days	129
5%	2.0			seven days	185
5%	2.0	18.00	1.8% lime	one day	231
5%	2.0	18.00	1.8% lime	three days	212
5%	2.0	18.00	1.8% lime	seven days	231
5%	2.0	18.00	3% lime	one day	251
5%	2.0	18.00	3% lime	three days	244
5%	2.0	18.00	3% lime	seven days	254
5%	2.0	18.00	4% lime	one day	261
5%	2.0	18.00	4% lime	three days	238
5%	2.0	18.00	4% lime	seven days	238
5%	2	18.00	5% lime	one day	281
5%	2	18.00	5% lime	three days	304
5%	2	18.00	5% lime	seven days	297

used as the secondary additive for the engineering evaluation of all epoxy-soil mixtures in the phase 2 investigation.

Figure 9 and Table 8 show that the maximum immersed strength obtained for dune sand is at the lowest volatile content. Those points were erratic rather than ordered and a smooth curve could not be drawn through the points. The maximum strengths obtained are approximately the same for 3, 4, and 5 percent epoxy contents. When the volatile content was increased by adding more water to the mixtures, the immersed strengths obtained would decrease. The rate of strength decrease with the increasing volatile content was greater for higher percentages of epoxy. The minimum immersed strength for 4 and 5 percent epoxy was at a volatile content of approximately 6 percent; while for 3 percent epoxy, the volatile content is 8 percent for minimum strength.

Both lime and cement were tried as additives for the sand-epoxy mixture in order to make higher immersed strengths. Figure 10 and Table 9 show the immersed strengths obtained with different combinations. The maximum immersed strengths of epoxy-sand specimens in Figure 9 and Table 8 were obtained from mixtures in which no extra water was added during mixing. However, the same rule could not apply to the epoxy-lime sand mixtures; if no extra water was added to the epoxy-lime-sand mixtures, the specimens would slake after immersing in water. The experiment showed that 1 or 2 percent water was necessary for the epoxy-lime-sand mix. Further tests indicated that the water should be added and mixed with lime-sand mixture before the prepared epoxy was used. This is the same procedure of molding specimens suggested at the end of presentation and discussion of results in phase 1. The specimens

Table 8. Effect of guardkote 120 A, 120 B and lime on the properties of the dune sand (Lab. No. S-6-2).

120A %	120B %	V. C. %	Ave. Dried Density pcf	Method of Curing	Individual Strength	Immersed psi		Ave. Immersed Strength psi	Optimum V. C. for Strength %	Maximum Immersed Strength psi	Ave. Linear Shrinkage %	Ave. V. C. Retention %	Ave. Linear Expansion on Immersion %	Ave. Moisture Absorption on Immersion %
3	1.2	2.88	110.5	Seven days in room temp.	337	264	337	313	1.2 (no extra water was added)	353	-1.15	1.2	+0.20	16.7
3	1.2	5.14	110.9	and one day in distilled water.	330	386		358			-0.70	0.6	0.00	12.5
3	1.2	6.74	111.5	"	353	356		354			-0.80	1.0	-0.15	10.3
3	1.2	8.20	112.3	"	198	205	159	184			-0.77	0.9	-0.65	9.4
3	1.2	11.53	112.3	"	238	238		238			-0.60	1.6	-0.10	7.8
4	1.6	3.61	110.9	"	287	271	294	384	1.6 (no extra water was added)	356	-0.70	1.3	-0.13	14.6
4	1.6	5.92	112.4	"	225	238		232			-0.43	1.4	-0.13	9.5
4	1.6	8.62	112.1	"	376	264	330	323			+0.40	1.3	-0.23	7.2
4	1.6	10.68	114.0	"	310	205	271	262			-0.45	1.7	-0.18	3.3
5	2.0	2.13	112.5	Seven days in room temp.	320	327	320	323	2.12 (no extra water was added)	353	-1.00	2.0	+0.10	15.8
5	2.0	3.58	112.6	and one day in distilled water.	146	182	195	141			-1.00	2.5	+0.05	14.2
5	2.0	5.49	111.2		93	80	100	91			+0.40	1.7	0.00	12.9
5	2.0	9.43	113.6		179	133	159	157			-0.20	1.7	-0.20	7.2
3	1.2	1.16	108.7	"	379	353	337	353	1.2 (no extra water was added)	353	-0.44	0.7	+0.02	17.2
4	1.6	1.49	109.4	"	337	386	346	356		356	-0.25	1.3	+0.33	17.8
5	2.0	1.80	110.3	"	346	379	379	368		368	-0.57	1.4	+0.35	17.6

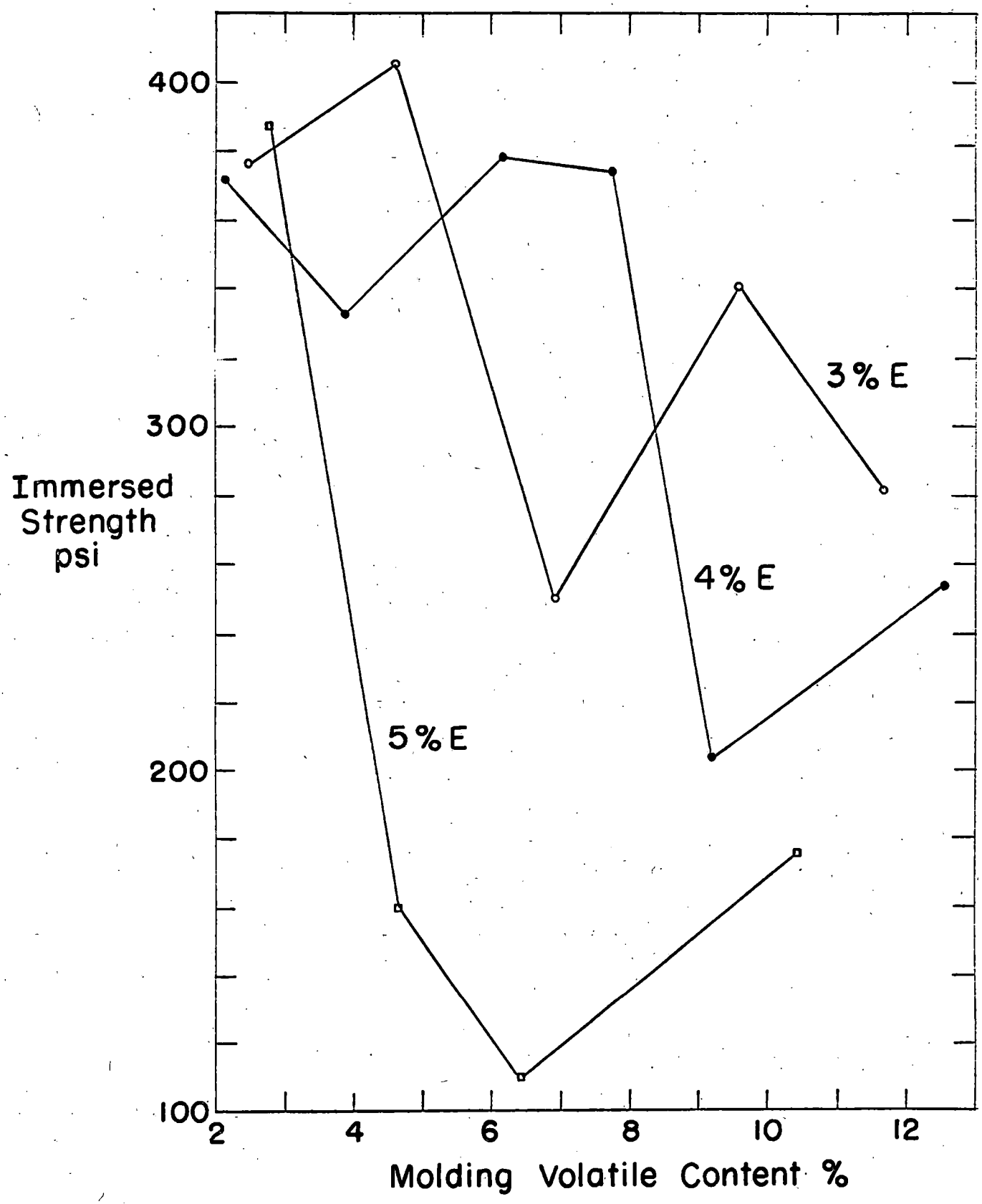


Figure 9. Molding volatile content -- immersed strength relationship for epoxy-dune sand mixtures.

Table 9. Effect of Guardkote 120 A, 120 B and different additives on the average immersed strengths of the dune sand (Lab. No. S-6-2).

120 A	120 B	Additive	Method of Curing	Ave. Immersed Strength, psi	V. C. %
3%	1.2%	2% lime	1 day in 40° oven, 1 day in distilled water	684	2.20
3%	1.2%	2% cement	"	532	1.70
3%	1.2%	3% cement	"	573	2.20
3%	1.2%	3% cement	1 day in 100% humidity rm. 1 day in distilled water	655	2.20
2%	0.8%	2% lime	1 day in 40° oven 1 day in distilled water	318	1.80
2%	0.8%	3% lime	"	373	2.80
2%	0.8%	4% lime	"	176	3.80

with 3 percent epoxy would have their strength increased by 92 percent if 2 percent lime was added as a second additive. The results are given in Table 10 and Figure 10.

A tentative explanation is given for the mechanism of the epoxy and epoxy lime stabilization based on the test results of the loess, gumbotil and sand specimens. Uncured epoxies are either honey-colored liquids or brittle-amber solids which become liquid when heated. Enlarged 10 million times, the molecules of resin might resemble short pieces that vary in length from one half inch in some of the liquid to several inches in the solids (21). These threads are joined together at the ends and along the sides to form large cross-linked structures after curing. Each molecule is tied to several others like the ropes of a fish net or the filaments of a spider's web, but in an irregular rather than uniform pattern. Since the epoxy resins are cured only by a romatic or aliphatic hydroxyls and various other organic radicals, it is believed that no chemical reaction has taken place between epoxy resins and various kinds of soil particles. But the epoxy resins successfully stabilize soils which have either ion exchange capacity or no ion exchange capacity; therefore there is evidence of attraction between the soil and the polymer. This attraction (14) could be caused by the electrically unsaturated ions on the surface of the soil particle attracting the ionic polymer (amine groups), aided by a secondary valence force between the soil and the polar groups of the polymer (epoxy and hydroxyl groups).

When the epoxy resin mixture alone is mixed with the dune sand, a coating of individual particles with resin solution is attained. The

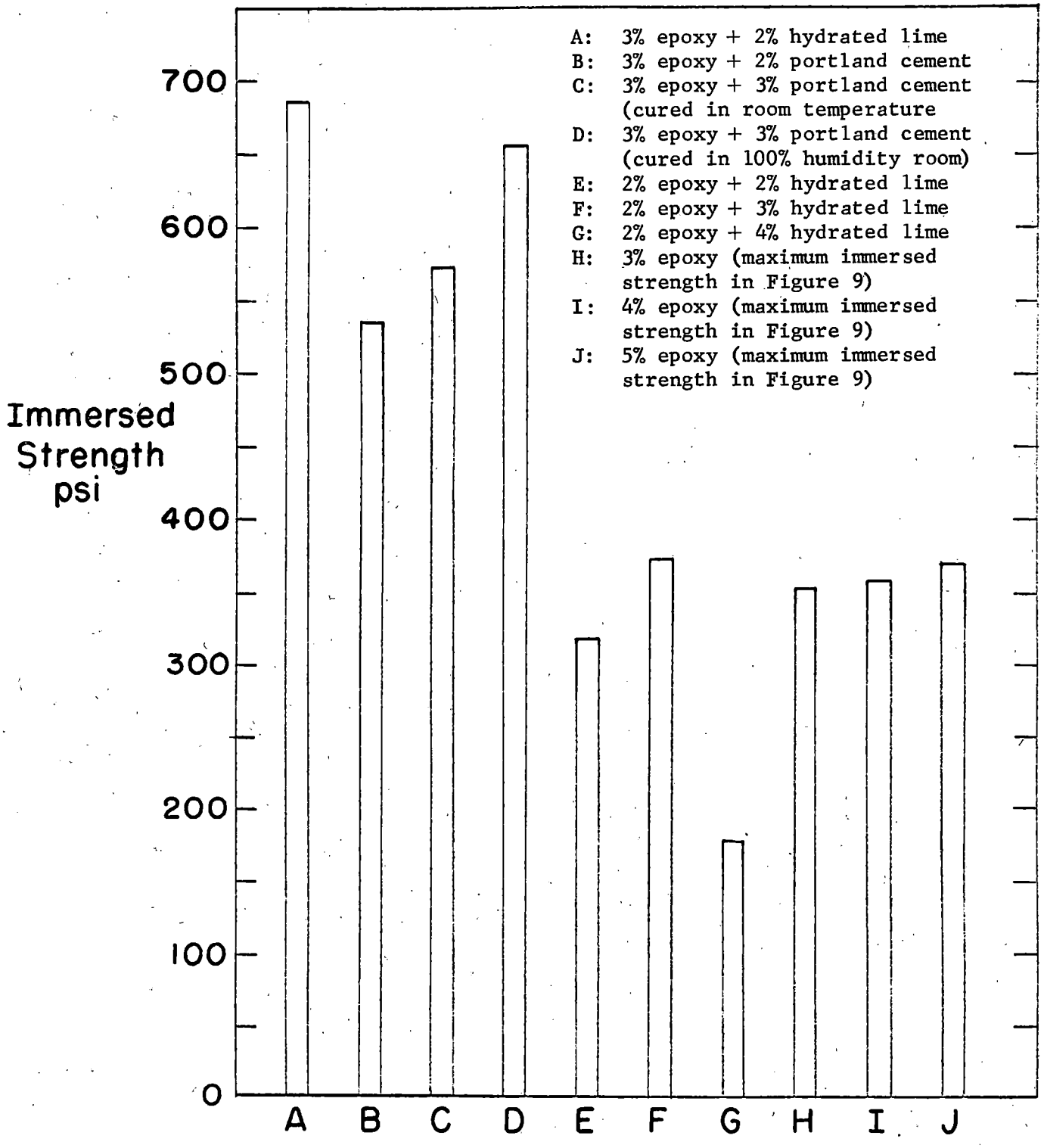


Figure 10. Effect of different additives on immersed strength of epoxy-sand mixture.

Table 10. Effect of Guardkote 120B and lime on the curing time and relative hardness of the cured epoxy resin.

$T = 80^{\circ}F$	120A parts by weight	120B parts by weight	Lime parts by weight	Curing time minutes	Relative hardness (by Shore Cleroscope)
	10	1	0	100	6
	10	2	0	25	550
	10	3	0	23	510
	10	4	0	20	350
	10	1	0.5	26	270
	10	1	1	22	510
	10	1	2	22	550
	10	1	3	22	170
	10	4	0.5	10	210
	10	4	1	10	250
	10	4	2	9	220
	10	4	3	7	330
	10	2	0.5	13	600
	10	2	1	13	620
	10	2	2	15	650
	10	2	3	15	610

epoxy is in contact with and adheres to the sand grains. When the cured epoxy hardens, it becomes a solid and binds the sand grains together.

The sand specimens yield a decreasing strength when water is added during mixing. Water is a non-solvent for epoxy mixtures. Tests showed that the addition of water to a prepared epoxy makes the epoxy gel float on the water surface. The individual sand grains will be surrounded by a film of water due to the hydrophilic character of grains, so the epoxy globules are prevented by the water film from coming in contact with and adhering to the sand grains. By the time the mixing water evaporates, the epoxy globules will already have set-up and the viscosity is so great it will stay somewhere between the sand grains which are less effectively bound than for the epoxy-sand specimens without the addition of water. If more water is used, thicker water films around the sand grains will be formed. This further reduces the probability of epoxy coming in contact with and adhering to the sand grains and it results in further strength decreases.

The maximum immersed strengths of dune sand specimens did not increase with increasing epoxy contents. The specimens containing 4 and 5 percent epoxy had approximately the same immersed strengths as the specimens with 3 percent epoxy content. Probably, 3 percent epoxy is enough to coat the individual sand grains with epoxy film. More epoxy makes the thickness of film increase, but it would not help the increase of strength.

When the epoxy is mixed with the friable loess, the volatile-strength relationship follows the usual pattern of increasing strength with increasing volatile content until a maximum is attained. Tests

in phase 1 have indicated that pre-emulsification of epoxy and hardener was not absolutely necessary; probably the clay fraction of soil acts as an emulsifying agent and thus aids the distribution of the resin in the water; thus the extra water mixed with soils prior to the addition of the prepared resin, enables a more thorough distribution of the dispersing epoxy resin particles through the mixture. After the epoxy resin particles set up, the solid epoxy adhers to soil grain or agglomerates of grains and bind them together. With higher volatile content the strength values will decrease due to the less effective compaction.

Hydrated calcitic lime has been found to be a very beneficial additive to improve the epoxy-soil mixture with higher immersed strengths. The friable loess specimens with 5 percent epoxy content would slake in water; they would give 470 psi maximum immersed strength when 2 percent hydrated lime was added. Specimens with 7 percent epoxy content had a 45 percent immersed strength increase after adding 2 percent lime to the mixture and those with 9 percent epoxy contents had a 70 percent strength increase.

The volatile-strength relationships of lime-epoxy-clayey soil mixtures follow the same patterns as the specimens of epoxy-clayey soil mixtures. The optimum volatile content for strength decrease with the increasing epoxy content. Soils which have higher clay contents require a higher optimum volatile content for strength. Each soil has a maximum volatile content beyond which satisfactory specimens cannot be molded. The limitations increase with the proportion of clay content.

When lime alone was used as a stabilizing agent with the friable loess, 2 percent hydrated calcitic lime gave 75 psi maximum immersed strength after seven days moisture curing. However, the specimens with 7 percent epoxy would have a 250 psi strength gain if 2 percent lime was added to the mixture and the specimens with 9 percent epoxy content would have a 700 psi strength increase. The effect of lime is therefore believed to be due to its effects on both soil minerals and the epoxy-hardener system. Lime may be expected to attack soil mineral surfaces and render them electrically more unsaturated and more polar; the properties of cured epoxy might also be changed by the action of lime; all resulting in better bonding and in an increase in strength.

The effect of lime on pure epoxy systems was investigated briefly by determining setting time, relative hardness and X-ray diffraction pattern of various epoxy, hardener and lime mixes. Results obtained (Table 10) indicated that setting time decreases in proportion to the percentage of lime. Relative hardness on the other hand increased markedly with lime for 10:1 epoxy hardener system, meaning savings from hardener can be realized by using a few parts of lime. For 10:2 epoxy hardener system, however, increase in hardness with lime was not so pronounced; whereas hardness of the 10:4 epoxy hardener system showed a significant decrease with lime producing set epoxy systems with moderate hardness. In the screening tests 10:4 epoxy hardener system was found most suitable for soil stabilization (Table 2). This combination when used for soil stabilization in conjunction with lime was found to produce higher stability. It may therefore be concluded that a moderate hardness results in better bonding. A possible explana-

tion for this follows:

The majority of resins and polymers show little or no crystalline nature in X-ray diffraction analysis (13). These substances formed with less degree of crystallization are called amorphous solids. In Figure 11, curve(a)shows the cured epoxy-hardener specimen has fair crystallinity, while curve(b)shows the same specimen with lime has less crystallinity. As the peak appearing in curve b was identified as $Ca(OH)_2$ according to the ASTM index (3), we can anticipate that lime affects the polymerization reaction and makes the epoxy resin less crystalline, and low hardness points out that the polymer has high ductility. A more ductile material is thus formed which can deform plastically to a greater extent than the epoxy resin specimen without lime. The higher ductility of resin could partially be responsible for increases in immersed strength of soil specimens. The lime left which shows in X-ray diffraction, becomes available for soil-lime reaction which gives rise to added strength.

Figure 12 shows volatile-dry density relationships for the friable loess-epoxy combinations. The optimum volatile contents for maximum dry densities are, on the average, 1 to 1.5 percent more than the optimum volatile content for strength. The maximum dry densities are seen to increase with increasing epoxy content. Figure 13 shows the relationships for volatile content-dry density for the friable loess-epoxy-lime combination. The optimum volatile contents for density and for strength are approximately the same for 5 percent epoxy content. For higher epoxy contents, the value of optimum volatile content is higher than that for immersed strength. An increase of 2 pcf in dry

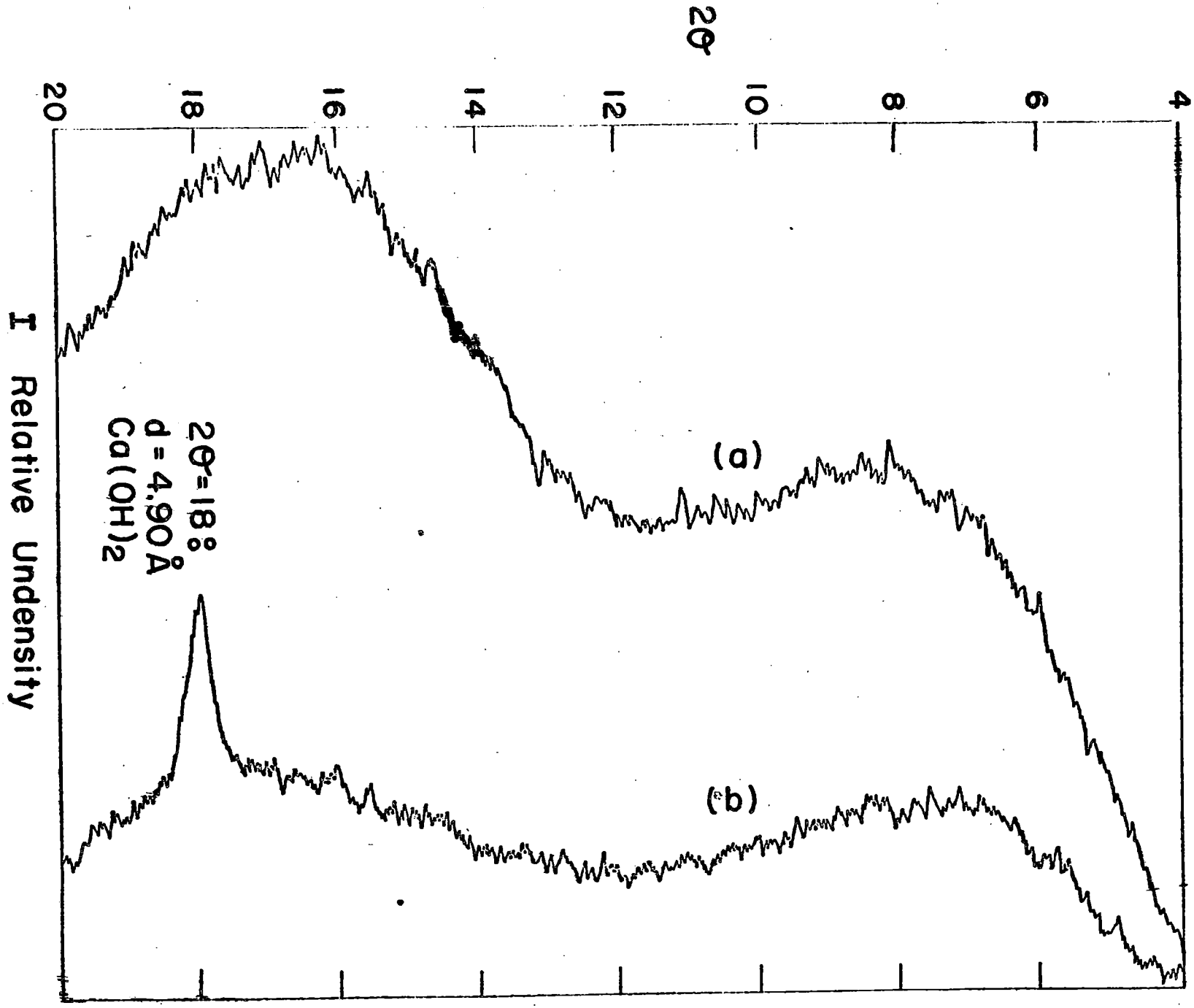


Figure 11. X-ray diffraction curves for: a) Epoxy: hardener 5:1 by weight, b) Epoxy: hardener: lime: = 5:1:1 by weight.

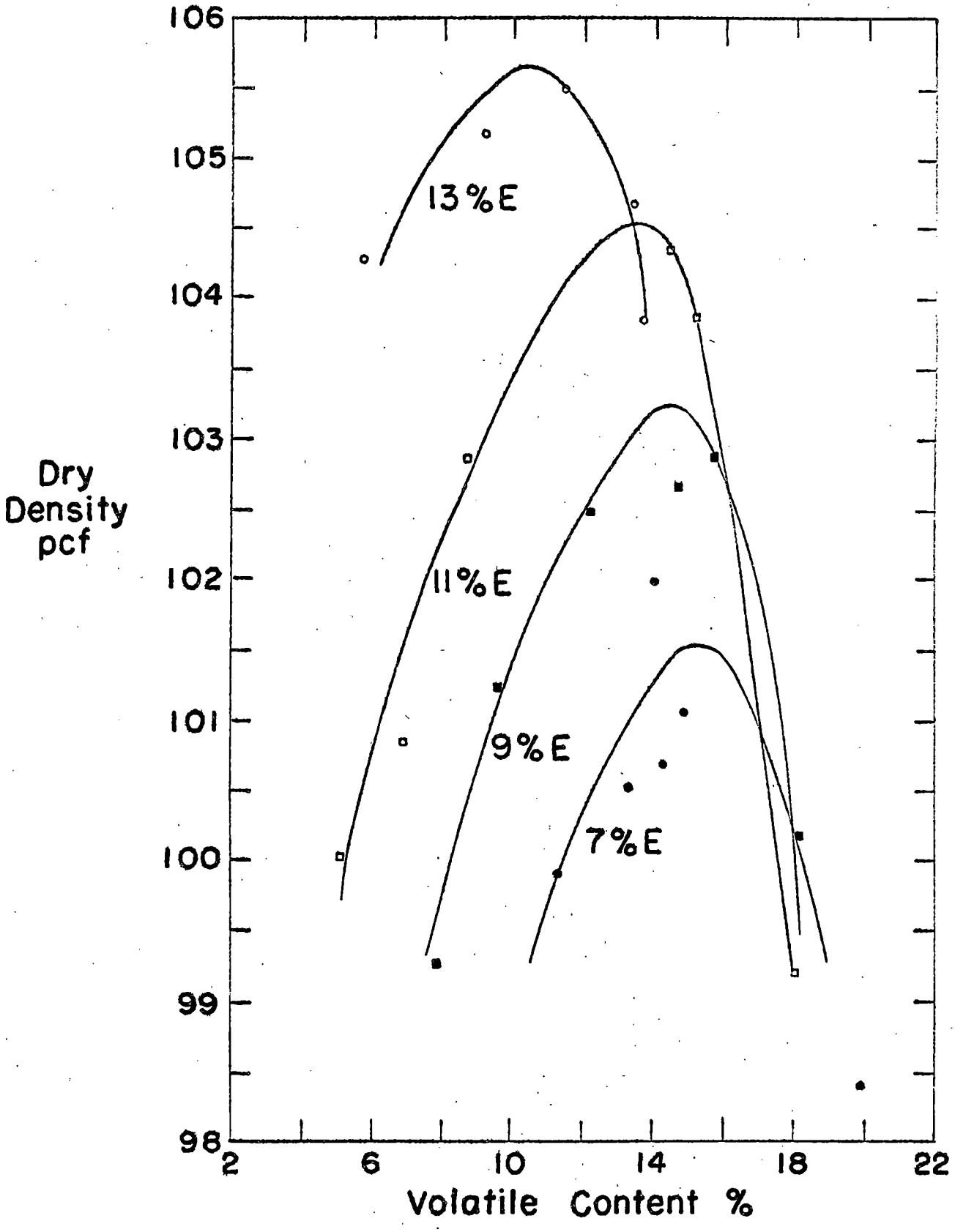


Figure 12. Molding volatile content -- dry density relationship for epoxy-friable loess mixtures.

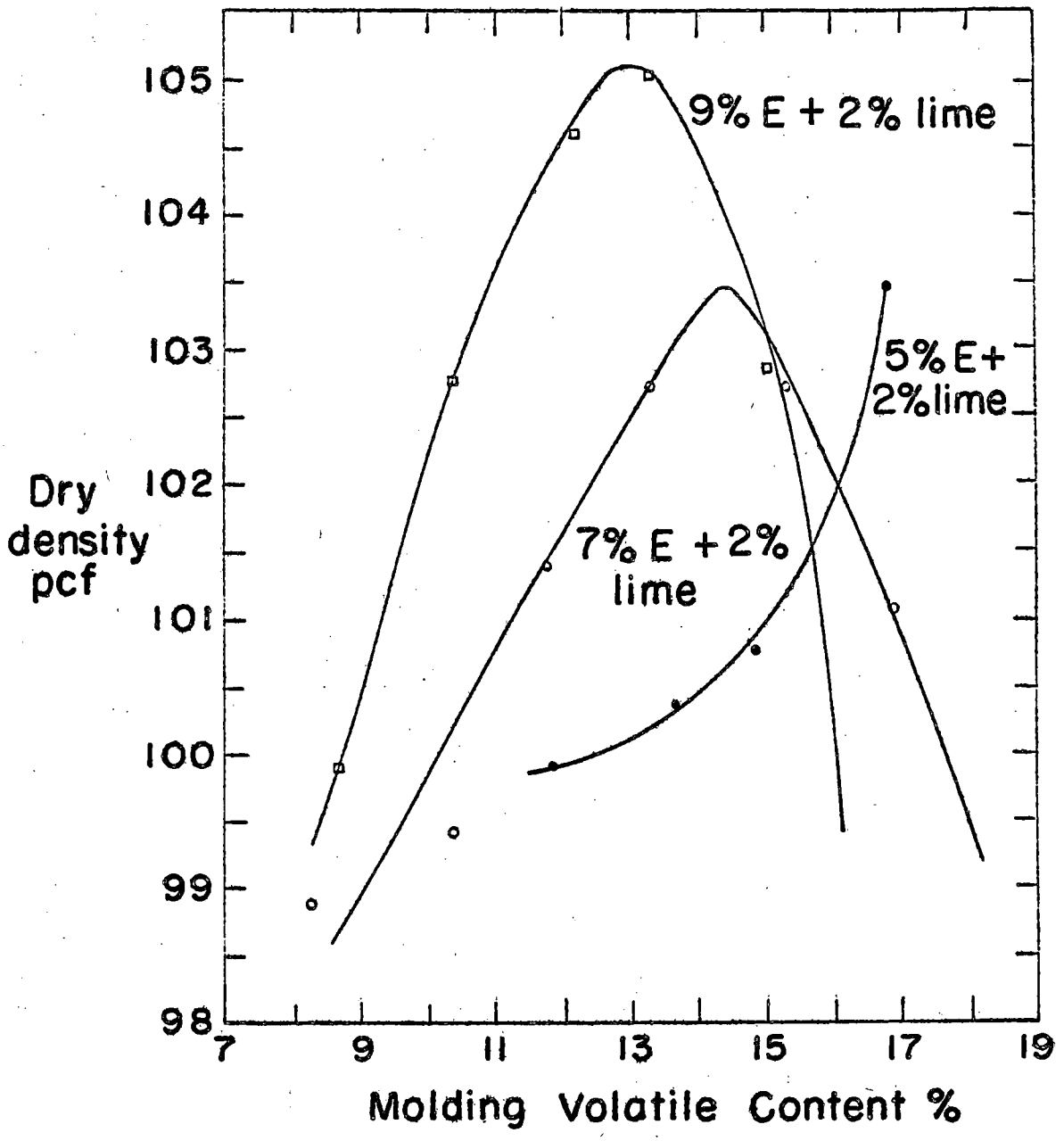


Figure 13. Molding volatile content -- dry density relationship for epoxy-lime-friable loess mixtures.

density is obtained if 2 percent lime is added to the epoxy-soil mixture.

The volatile content-dry density relationships for the plastic loess and gumbotil stabilized by epoxy and lime are presented in Figure 14. It was found that the maximum dry densities for different epoxy contents were approximately the same for plastic loess soil; while the relationships for gumbotil shows that the maximum dry density for the specimen with 5 percent epoxy content is greater by 2 pcf than that of the specimen containing 7 percent epoxy.

Effect on Shrinkage, Swelling and Moisture Absorption

The immersed strength, the shrinkage upon drying, and the expansion upon wetting are all important criteria of the engineering stability of a soil. Excessive deformations from drying, wetting and alternative freezing and thawing are symptoms of instability of soils. If these happen to a base or a subbase material, the excessive deformation can cause the road surface material to be damaged or cracked.

According to Roderick (18), allowable maximum linear expansion of the stabilized soil, used as a flexible highway base course, is 1.64 percent.

The data presented in Tables 3, 4, 5, 6, and 8 show that the four soils gave average linear expansion values which are far less than the 1.64 percent maximum allowed after immersion for one day. On the viewpoint of the allowable linear expansion upon immersion in water, they would be suitable as base course material when stabilized with the amount of epoxy used.

The absorption of water by cohesive soils causes swelling and conversely drying causes shrinkage. These volume changes have been studied for cohesive soils (11). It shows that the maximum changes in volume due

density is obtained if 2 percent lime is added to the epoxy-soil mixture.

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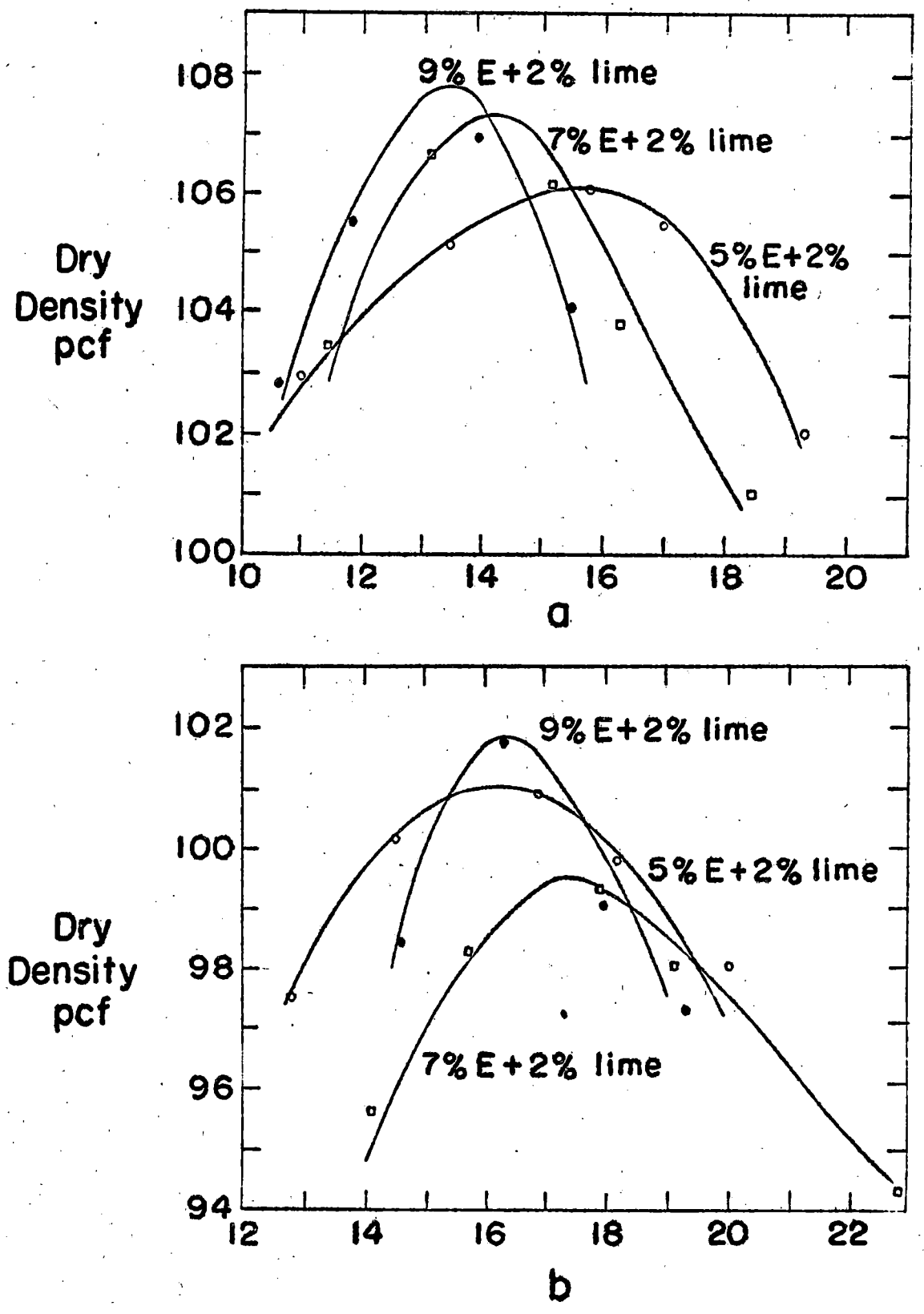

Figure 14. Molding volatile content-immersed strength relationship for epoxy

a. Resin-lime-plastic loess mixtures
b. Resin-lime-gumbotil mixtures.

to drying occurred when the specimens were made up in a saturated condition. But the minimum changes in volume due to swelling occurred when the specimens were made up in saturated condition. It is therefore considered advisable to compact cohesive subgrades below their optimum moisture content in cases where they are likely to be subject to evaporation of moisture during the life of the road and above their optimum moisture content in case the ingress of moisture is likely to occur during the life of road.

The results presented in Tables 3, 4, 5 and 6 show that the average linear shrinkages of the three soils are less when their volatile contents are at or below optimum for strengths; the average linear expansions on immersion are less when their optimum volatile contents are at or above optimums for strength. It is concluded that the same rules which were suggested above should be applied to the epoxy-lime stabilized soils during construction.

For cement stabilized soils used as a paving material, a recommended requirement with respect to absorption is that the maximum moisture content at any time during wet-dry or freeze-thaw tests shall not exceed the quantity which will completely fill the voids of the specimens at time of molding. The maximum dry density of the friable loess specimen containing 9 percent epoxy, from Figure 10, is about 106 pcf. The specimens would weigh $\frac{A \cdot h}{12^3} \times 106 \times 454$ gram. Where A is the cross-sectional area of the specimens in square inches, h is the height of the specimen in inches. Therefore, the 2 by 2 inch specimen would weigh $\frac{\pi(2)^2 \times 2}{4 \times (12)^3} \times 106 \times 454 = 175$ gm. If the specific gravity of the soil is assumed to be 2.65, the solid space of the soil in 2 by 2 inch specimen would be equal $\frac{175}{2.65}$ cm^3. In case the void space is filled with water, the maximum water content should be equal to $\frac{37}{175} = 21$ percent.

The average moisture absorptions are all less than 21 percent after immersion. They are suitable as paving materials on the basis of absorption of water.

Frost Susceptibility

The deformation and the reduced strength caused by alternative freezing and thawing tests are the main measurements in the evaluation of frost susceptibility. The Iowa Freeze-Thaw Test (12) was used with specimens prepared from the raw soil and the selected mixtures. All raw soils except sand bulged and were completely destroyed at the end of the 10th cycle. Figure 15 shows the treated and untreated specimens after three cycles of alternative Freeze-Thaw Test. The treated soils contained 7 percent epoxy and 2 percent hydrated lime except dune sand which was stabilized by 3 percent epoxy and 2 percent lime. The results of the test are tabulated in Table 11. There was almost no detectable heaving of epoxy-lime dune sand specimens after 10 freeze-thaw cycles. Both linear expansion and the strengths obtained from freeze-thaw specimens were affected by the percentage of clay content. The specimens with more clay yielded more linear expansion and lower strength than those with less clay content. The linear expansion for the freeze-thaw specimens were 0, 0.25, and 3.17 percent for the friable loess, plastic loess and the gumbotil, respectively. When subjected to the freeze-thaw test, specimens for friable loess, plastic loess, gumbotil and dune sand had average strengths of 820, 677, 366, and 672 psi, respectively. These are 97.5, 83.5, 61 and 98.5 percent of maximum immersed strengths

Table 11. Effect of freezing and thawing on untreated and treated soils.

	Friable Loess 2% Lime + Epoxy Resin Content, %		Plastic Loess Epoxy Resin Content % + 2% Lime		Gumbotil Epoxy Resin Content % + 2% Lime		Dune Sand Epoxy Resin Content % + 2% Lime	
	0	7	0	7	0	7	0	7
Molding volatile content, %	18.85	9.66	15.09	15.03	20.35	18.44	3.64	2.96
Dry density, pcf	106.06	100.65	106.45	105.75	104.87	99.48	105.27	111.70
Linear expansion after 10 cycles of freeze-thaw, %		0		0.25		3.17		0
Linear expansion after 11 days immersion, %	--	0.40	--	0.73	--	0.80	--	0.30
Volatile after 10 cycles of freeze-thaw, %	31.25	2.25	29.54	4.07	32.03	3.48	20.85	1.82
Volatiles after 11 days immersion	--	16.80	--	18.17	--	21.05	--	17.67
Unconfined compressive strength after 10 cycles of freeze-thaw (Pf) psi	--	820 (840)	--	677 (810)	--	366 (600)	--	672 (684)
Unconfined compressive strength after 11 days immersion (Pc) psi	--	708	--	730	--	463	--	598
Index of resistance to freezing $R_f = \frac{Pf}{Pc} \times 100\%$	--	115.8	--	92.7	--	79.1	--	112.4

obtained by these soils (Tables 4, 5, 6, and 8) at identical epoxy contents. Gumbotil was affected most severely both in expansion and unconfined compressive strength when subjected to alternate freezing and thawing.

California Bearing Ratio

The California Bearing Ratio test, usually shortened to CBR, is another way to determine the stability of the base course for flexible pavements. The main purpose of a base course in flexible pavement design is to provide a stress-distributing medium which will spread the load applied to the surface, so that shear and consolidation deformations will not take place in the subgrade. Table 12 shows the results of CBR tests performed on untreated 20-2 soil and on soil 20-2 treated with epoxy. The CBR value of the untreated specimen was 10. The CBR value of the specimen treated with 7 percent epoxy and 2 percent lime is approximately 40 times that of the untreated specimen.

The linear expansion for the treated specimen was constant after soaking 25 hours in water. Linear expansion of the untreated specimen was approximately 27 times that of the treated specimens after soaking 96 hours in water; the small linear expansion shows that water proofness was obtained by the treatment.

California Bearing Ratio values for lower epoxy contents were estimated by assuming proportionality between CBR values and epoxy contents. The assumption was based on observed proportionality between unconfined compressive strengths and epoxy contents.

Table 12. Effect of epoxy resin on California Bearing Ratio and related properties of the friable loess.

Epoxy 120 A %	120 B %	lime %	Dry density of molded specimen pcf	Volatile content during molding, %	Moisture retention after curing %	Moisture absorption after 4 days soaking %	Expansion of specimens during 4 days soaking elapsed time, hours	Expansion %	CBR at 0.1 penetration after 4 days soaking
0	0	2	10664	17.88	*16.02	18.19	0	0.000	
							1	0.007	
							25	0.038	
							48	0.047	
							72	0.053	
							96	0.055	10
7	28	2	106.75	9.80	**7.94	13.78	0	0.000	
							1	0.001	
							25	0.002	
							48	0.002	
							72	0.002	
							96	0.002	410

* The specimen was cured at room temperature for one day period.

** The specimen was cured at 104^{o}F oven for one day period.

The estimated CBR values for 1 and 2 percent epoxy content are given below.

Soil	Epoxy content %	Lime content %	CBR
20-2	1	2	50
20-2	2	2	100

THE APPLICATION OF EPOXY STABILIZATION TO PAVEMENT CONSTRUCTION

Pavements may be classified as flexible or rigid. The main difference between the two types of pavements is the manner in which they distribute the load over the subgrade. Due to the rigidity and high modulus of elasticity the rigid pavement tends to distribute the load over a relatively wide area of soil. A major portion of the structural capacity is supplied by the slab itself. The flexible pavement, on the contrary, distributes the load over a relatively small area and consists of layers which will resist the load distributed through them; therefore the highest quality materials are near the surface.

If soil (20-2) stabilized by epoxy and lime is considered to be the material for a flexible pavement (subbase, base and surface course material), the pavement may be designed by the following criteria:

I. Unconfined Compression Test Design

The thickness of flexible pavements are built to such a depth that stress on any given layer will not cause undue rutting, shoving and other differential deformations resulting in an uneven surface. In other words, the thickness is determined by the total load applied at the surface and in part by the strength characteristics of the subgrade. A formula derivable from Boussinesq's equation for thickness design is given below (10)

$$T = \left[\left(\frac{q}{q - p} \right)^{2/3} - 1 \right] \pi Z^2$$

where T = the steel load

q = load intensity on loaded area

p = the vertical pressure transmitted to the surface at depth Z.

Assuming q = t = 70 psi where t is inflation pressure, the above equation then becomes*:

$$T = 220 \left[\left(\frac{70}{70 - p} \right)^{2/3} - 1 \right] z^2$$

The maximum immersed strength for the specimen of 20-2 soil containing 5 percent epoxy and 2 percent lime is 470 psi. Taking the immersed strength proportional to the spoxy content the specimen of 20-2 soil with 1 percent epoxy and 2 percent lime would have 94 psi immersed strength. According to Terzaghi (23), the ultimate bearing capacity for cohesive soil in footing design is approximately 3.5 times that of pressures which cause the specimen to fail. Therefore, the bearing capacity for 1 percent epoxy and 2 percent lime combination for 20-2 is 320 psi. If the highway is constructed within Iowa, the bearing capacity should be reduced to 329 x 97.5 = 320 psi according to the reduction from Iowa Freeze-Thaw Test results. Further, if the factor of safety for bearing capacity is 5 the maximum bearing capacity of 20-2 after stabilizing with 1 percent epoxy and 2 percent lime is 64 psi. Then from the formula given above (10) setting p = 64 the protective layer for 16,000 wheel load (T) is 4 inches.

II. CBR Design

Base materials for flexible pavements are required to have design CBR values not less than 80 (26). If a 16,000 lb wheel load is selected

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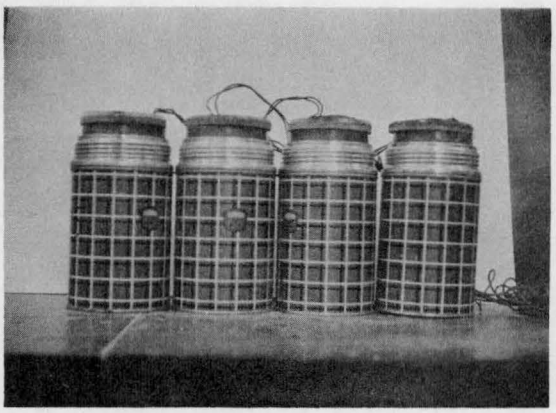
* The formula is not applicable beyond t = 70 and z = 0.

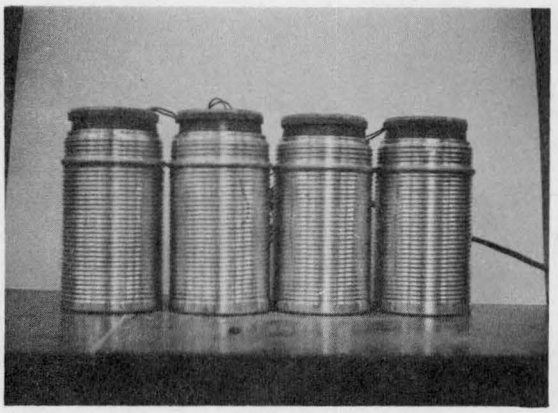
as a maximum wheel load for commercial vehicles on highways and if the natural subgrade at construction site has a CBR value of 6, the thickness of the required protective layer lying above the natural subgrade is 19 inches. The thickness was obtained from Figure 15 which was developed by the Corps of Engineers for the design of flexible highways. The CBR value of the natural subgrade would rise up to 10 after compaction (Table 12). Then the protective layer above the compacted subgrade would require 14 inches. The relative thickness is shown in Figure 17. The thickness design may be latered if different materials are available at the construction sites. They are discussed in the following different cases.

a. If subbase material with a CBR value of 40 is available near the construction site, or if the subgrade soil can be stabilized up to a CBR of 40 by adding 1 percent epoxy and 2 percent lime, the necessary protective layer would be 7 inches over the subbase as shown in Figure 18a.

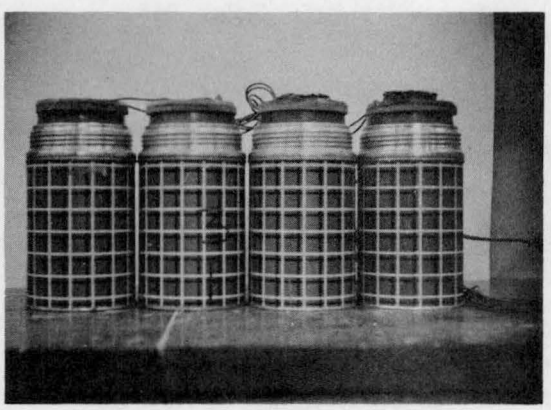
b. According to the predictions of the CBR test, 2 percent epoxy and 2 percent lime can bring 20-2 soil up to a CBR value of 100. If this stabilized soil were used as a base material, the necessary surface thickness is 4 inches. Whem compared with unconfined compression test design this result corresponds to a safety factor of 5. The cross-section is shown in Figure 18b.



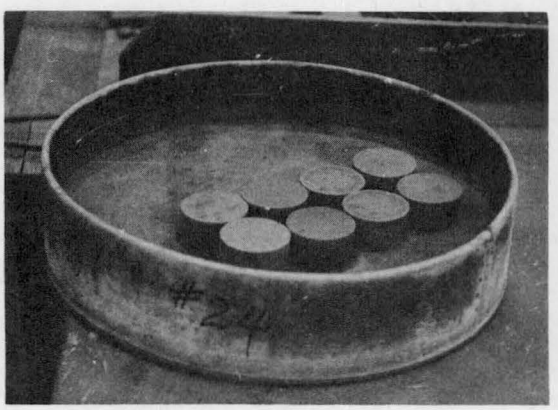
(a) Friable loess -- the two specimens on the right were untreated; the other 2 specimens contained 7 percent epoxy and 2 percent lime.



(b) Plastic loess -- the 2 specimens on the right were untreated; the other specimens contained 7 percent epoxy and 2 percent lime.



(c) Kansas gumbotil -- the 2 specimens on the right were untreated; the other 2 specimens contained 7 percent epoxy and 2 percent lime.



(d) Four pairs of the treated specimens from four kinds of soils remained intact in the water after immersing 11 days.

Figure 15. Effect of three cycles of alternal freezing and thawing on untreated and treated soil specimens.

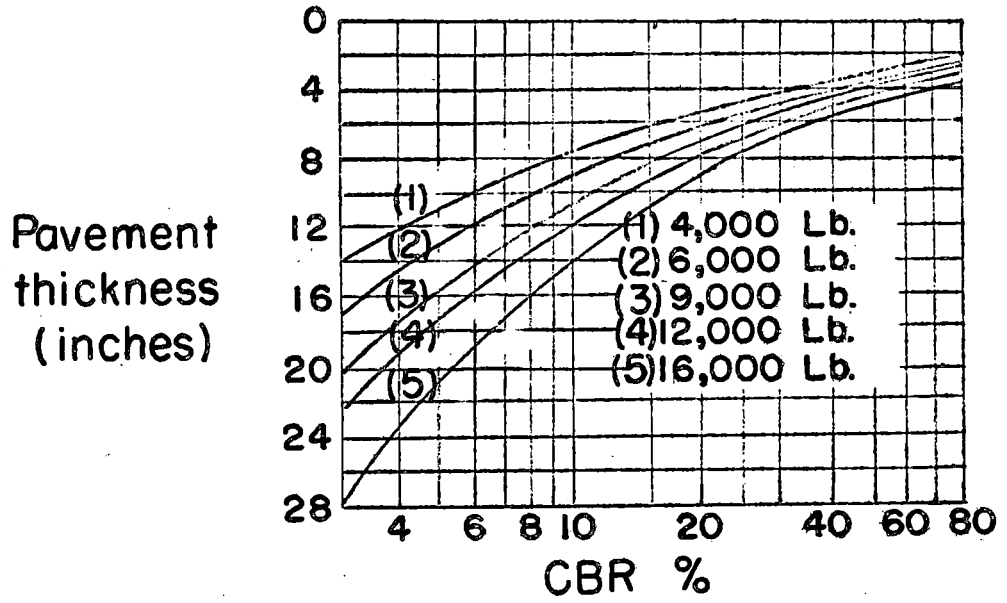


Figure 16. Design curves for flexible highways by Corps of Engineers (from Yoders, Principles of Pavement Design) (21).

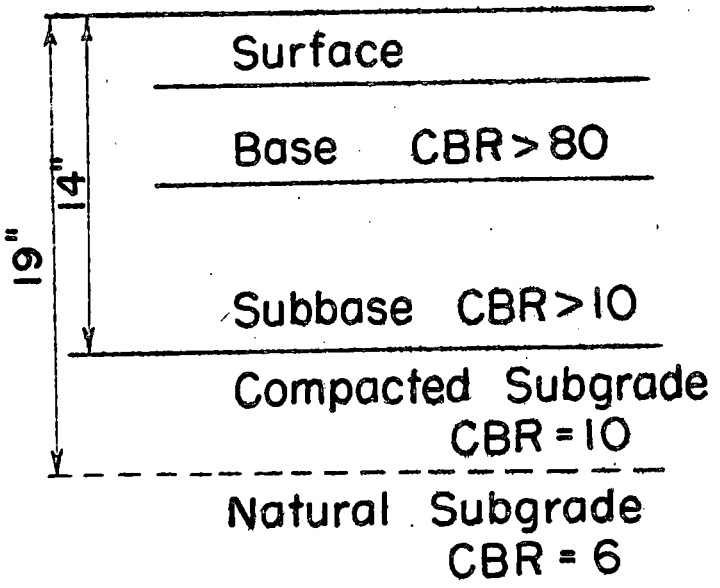


Figure 17. Pavement thickness for 16,000 wheel load, based on CBR value.

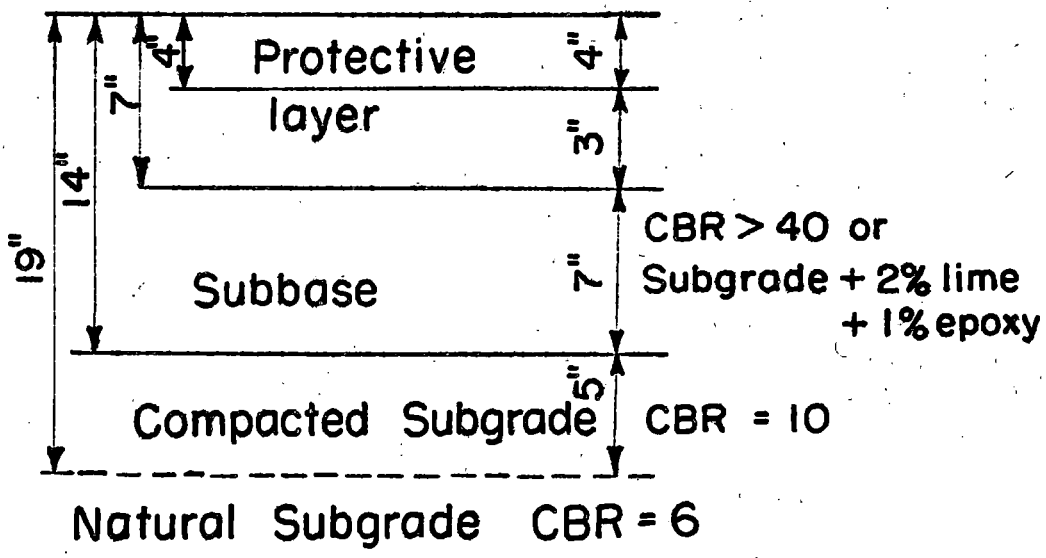


Figure 18a. Pavement thickness for 16,000 lb. wheel load on friable loess based on CBR value of epoxy -- lime stabilized subbase.

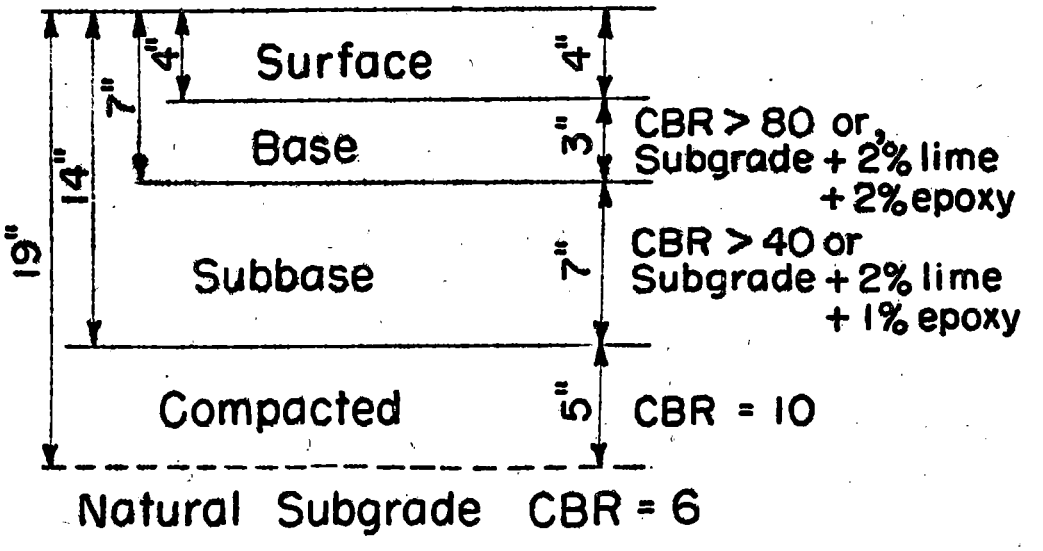


Figure 18b. Pavement thickness for 16,000 lb. wheel load on friable loess based on CBR value of various epoxy-lime contents.

Wearing Surface Material

The data obtained with epoxy-lime-soil specimens in unconfined compression and CBR tests suggested the evaluation of the mixtures' suitability as wearing surface materials. The chief function of a surface course is to provide a smooth surface resistant to traffic and to impart some shearing resistance to the pavement with added resistance to deformation.

The Hveem Test, developed by the California Division of Highways, utilizes a stabilometer and a cohesiometer to test the friction and cohesion of flexible-pavement materials. The deformation in the stabilometer test is expressed as a function of the ratio of the transmitted lateral pressure to that of the applied vertical pressure. With selected epoxy-lime contents, mixtures were molded and tested according to the specification of test method No. Calif. 301-A (22). The compaction of the test specimen was accomplished by means of the mechanical compactor which imparts a kneading action consisting of a series of individual impressions made with a ram having a face shaped as a sector of a 4 inch diameter circle. A 350 psi pressure was applied with a kneading action one hundred times to each 2 1/2 by 4 inch specimen. The specimens were cured by the method described in phase 2 and immersed in 140^{o}F water for half an hour prior to testing.

Cohesion was measured by means of the Cohesiometer test. The test was run according to the specifications of No. Calif. 306-A (22).

The results of the two tests are presented in Table 13. The suitability of the plant-mixed surfacing by the Hveem method is deter-

Table 13. Effect of epoxy and lime on Hveem Test and related properties of friable loess

Epoxy 120A %	120B %	Calcitic hydrated lime %	Volatile content during molding %	Dry Density pcf	Stabilometer value R	Cohesiometer C
9	3.6	2	10	115	96 *	grams per inch width with corrected to a 3 inch height
				115	95 *	1172
						1085
				117	66 **	950
				116	78 **	--

* from formula $R = 100 \frac{100}{\frac{2.5}{D}\left(\frac{Pv}{Ph} - 1\right) + 1}$ for soil only

Pv = 160 psi vertical pressure

D = turns displacement reading

Ph = horizontal pressure during 160 psi vertical pressure

** from formula $R = \frac{22.2}{\frac{PhD}{Pv - Ph} + 0.222}$

Pv = 400 psi vertical pressure

Ph = horizontal pressure during 400 psi vertical pressure

mined on the basis of whether or not the asphalt content and aggregate grading will satisfy the following requirements (4).

	Light Traffic	Medium Traffic	Heavy Traffic
Stabilometer Value R	30+	35+	37+
Cohesimeter Value C	50+	50+	50+

No specification has been established for epoxy-stabilized mixtures. However, both R and C values obtained from epoxy stabilized soil mixtures are far greater than the values presented above for heavy traffic conditions for asphalt surfacing courses.

Traffic Simulator for Checking Behavior of Epoxy-Lime-Soil Mixtures

The Traffic Simulator test was devised primarily as a check on the behavior of paving mixes under a moving load. The equipment was developed by the Bituminous Research Laboratory, I.S.U. (7). The six specimens used in this test were identical with those used in Hveem stability tests. An oscillating carriage provided loading on the test specimens with a moving wheel. Only one way traffic over the test specimens was simulated. Forty pounds load was used in the tests conducted because this load provides an equivalent of 80 psi tire loading on the specimens. Generally, evaluations and comparisons of the behavior of mixes have been based on the specimens after 5,000 passes. Mixes that show a displacement of more than 1/8 inch at or before 5,000 passes are arbitrarily deemed suspect to distress under traffic. The test was conducted at room temperature. Distilled water was sprayed, by hand, on the tops of No. 1 and No. 2 specimens shown in

Figure 15 during operation in order to investigate whether or not the specimens would be affected by a moving load during wetting.

Since the inside diameters of the specimen holding rings were slightly over 4 inches, the specimens fitted loosely in the rings. The No. 2 and No. 6 specimens were tightened by inserting metal shims around their sides. The other four samples were tightened by nails, as shown in Figure 19. When the carraige rebounded due to the thrush springs in the ends, the specimens tightened by nails gradually loosened and hit the cover. After 8,550 passes the surfaces of the loose test specimens deteriorated to the point of failure. Tight specimens (No. 2 and No. 6), however, remained intact with no evidence of failure. The average deformations of No. 1 and No. 2 specimens, measured by Ames dials, were 0.03 and 0.025 inches after 8,550 and 5,000 passes (corresponding to 1.2 and 1.0 percent deformations), respectively. In comparison with the results obtained by Csanyi (7), the specimen with 9 percent epoxy had less deformation than those asphalt Ocheydan aggregate mixes containing 4 to 8 percent asphalt.

Flexural Strength

If epoxy-soil mixes are treated as rigid pavement materials, the flexural strength, or the modulus of rupture, for each specimen might be determined by the beam breaking test. The molding and testing procedure was based on the method of test for flexural strength of soil cement, using a simple beam of 3 by 3 by 11 1/4 inch size with third point loading, suggested by Felt and Abrams in ASTM (1). The beam was molded with a dry density of 106 pcf which is the maximum

dry density of the 20-2 specimen containing 9 percent epoxy obtained in the phase 2 investigation. The beam was cured one day in a 104°F oven and soaked in water for 24 hours prior to testing. The modulus of rupture for the specimen of 20-2 soil with 9 percent epoxy content was calculated to be 225 psi after testing. A specimen of the same soil with 15 percent Portland cement, molded and tested as a dry soil beam by Tinoco (24) yielded a modulus of rupture of 140 psi. The value of modulus of rupture from the epoxy-lime-soil beam was inferior when compared with that of concrete pavement material which ranges from 600 to 750 psi (17).

The results of Hveem, traffic simulation, and flexural strength tests suggest that epoxy stabilized soil may be used as a semi-rigid surface coarse material.

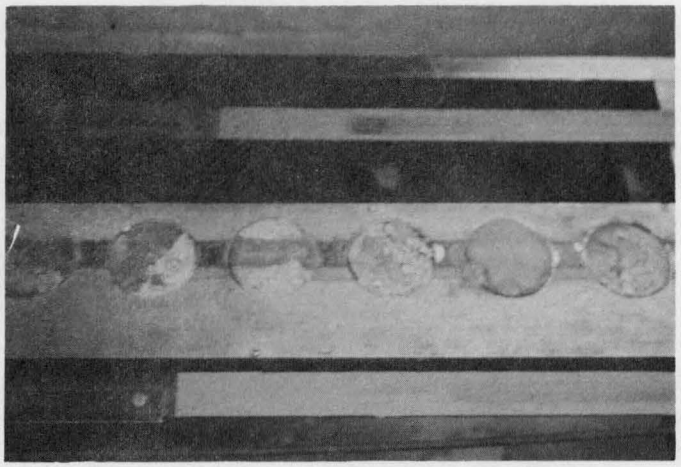


Figure 19. Effect of 8,500 passes of the Traffic S. T. on six specimens, which were numbered from the right specimen to the left.

FURTHER INVESTIGATION OF MIXING ORDER

When lime was mixed directly with a prepared epoxy-hardener solution prior to adding the mixture to the soil, the specimen would yield greater immersed strength than the specimen molded with the mixing order presented in the phase 2 investigation. In other words, the following mixing order for soil-epoxy-lime mixes was the best one so far investigated for getting good immersed strength.

1. Air dry soil with the required amount of distilled water was mixed with a Hobart model C-100 mixer at low speed for one minute and was then hand-mixed.

2. Two percent calcitic hydrated lime based on the oven dry soil weight was added to the prepared epoxy-hardener mixture. The mixture was then stirred with a spatula to insure a uniformity before using.

3. The soil-epoxy-lime mixture was then mechanically mixed for two minutes, followed by hand-mixing for a minute.

A preliminary investigation showed that the specimens of friable loess containing 7 percent epoxy and 2 percent lime had 22 percent strength gain if the above mixing order was used rather than the mixing order presented in phase 2 investigation. This procedure of mixing is suggested for further study on epoxy-lime stabilization.

CONCLUSIONS

The following conclusions were reached on the basis of this investigation on four different soils:

1. After the soils were stabilized with various percentages of epoxies, all were found suitable as base course materials. Traffic Simulator Tests have shown that the resistance of epoxy-treated soils against the abrasive action is excellent, therefore epoxy or epoxy-lime stabilized soils may be tried as a road surface material.

2. The effectiveness of epoxy treatment depends on the clay content. High clay contents give the least satisfactory results. The epoxy stabilization is most effective for the friable loess.

3. All soils used in this investigation were improved in immersed strengths by the addition of lime to the soils to be stabilized by epoxy.

4. Epoxy affects soils in two ways: (1) it reduces the moisture affinity of clays by surface chemical action, and (2) it imparts cementation, thereby producing a semirigid soil framework. The lime is believed to be an agent which causes the cured epoxy to be a more ductile material. This may be responsible for increased immersed strengths of soil specimens.

5. The higher the curing temperature, the faster the setting of epoxy stabilized soil. Curing temperatures between $30^{o}F$ and $104^{o}F$ were found most practical for curing epoxy stabilized soil specimens. The short curing time for epoxy makes it an ideal stabilizing agent for emergencies. The epoxy dune sand mixtures with lime could be hardened

at 80°F in half an hour.

6. Because of the high-cost epoxy ($0.60 per pound) compares unfavorably with other methods of soil stabilization. However the cost of epoxies has shown a very rapid decline. If this trend continues epoxy may be an economic stabilization agent for future.

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